SENSOR TECHNOLOGY ASSESSMENT FOR ORDNANCE AND EXPLOSIVE WASTE DETECTION AND LOCATION

March 1, 1995

Prepared for

U.S. Army Corps of Engineers
Huntsville Division
Explosive Ordnance Engineering MCX and Design Center
Huntsville, Alabama

and

Army Yuma Proving Ground
Yuma, Arizona

Through an Agreement with
National Aeronautics and Space Administration

by

JPL

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL D-11367 Revision B

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DEPARTMENT OF THE ARMY
HUNTSVILLE DIVISION. CORPS OF ENGINEERS
P.O. BOX 1600
HUNTSVILLE. ALABAMA 35807-4301

REPLY TO
ATTENTION OF

February 2, 1995

Mandatory Center of Expertise
for Ordnance and Explosive Waste
(CEHND-PM-MC)

Mr. John Peterson
Jet Propulsion Laboratory (JPL)
4800 Oak Grove Drive
M/S 525-3660
Pasadena, California 91109

Dear Mr. Peterson:

This letter is to acknowledge JPL's intent to distribute JPL document D11367 entitled, "Sensor Technology Assessment for Ordnance and Explosive Waste Detection and Location," which was commissioned by the U.S. Army Corps of Engineers, to foreign countries and/or foreign nationals. The cover and title page should be annotated: "Distribution Statement A. Approved for public release; distribution is unlimited."

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Sincerely,

K. A. Edmundson

K. A. Edmundson, P.E.
Director of Programs and
Project Management

A

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The work described herein was carried out by the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the U.S. Army Corps of Engineers, Huntsville Division, Ordnance and Explosive Waste (OEW) Mandatory Center of Expertise (MCX) and by the U.S. Army Yuma Proving Ground, under an agreement with the National Aeronautics and Space Administration, Contract NAS7-1260.

This document has been reviewed for export compliance and has been classified under the Department of Commerce, Export Administration Regulations, export control commodity classification number (ECCN) 6E96G. This will allow export under the general blanket GTDU.

All product information contained in this report was provided by the respective vendors, and as such contain their respective points of view. Since this report is designed to assess technology rather than vendors, no comprehensive validation of vendor claims was performed. The appearance of product names does not imply endorsement.

The prices listed in this report were provided by the vendors during discussions to obtain technical information and could differ at the time of reading, and may be subject to change. Contact the respective vendors for current specifications and up-to-date price lists.

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Sensor Technology Assessment for Ordnance and Explosive Waste Detection and Location

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REVISION B ENHANCEMENTS

This revision reflects information made available through the efforts of the many reviewers of the initial document release (revision A), and supersedes all previous versions. The initial release was reviewed by numerous vendors, participants of the "Unexploded Ordnance Detection and Range-Remediation" Conference (held in Golden, Colorado May 17-19, 1994), personnel from the U.S. Army Corps of Engineers, Yuma Proving Ground personnel, and other interested individuals.

We received 15 separate inputs containing comments for a total of 55 different issues. All issues were assessed for validity and potential to enhance the document. Of the 55 issues, 38 were considered to have a significant impact on the document and could readily be incorporated within currently available resources and allow the next scheduled publication to be delivered on time. The remaining issues were either: 1) later rescinded by the original requester and the removal agreed upon by the study team, or 2) the effort to include the additional information was not justifiable for the intended usage of the document.

In addition, to help validate the information contained in the initial release, letters were sent to a random sample of the vendors (those not attending the UXO conference) whose products are described in the document, requesting validation of their information. The responses received were positive. The changes requested by the vendors were in general those associated with new or enhanced products that had been developed since our original contact with the vendor. In addition, some minor corrections to product measurement sensitivity and product features were identified. A few cases where the product name was a registered trademark were identified by vendors and we were requested to add the appropriate indication (an ®). All requested modifications have been incorporated.

Since many changes were made in numerous areas to make the document more comprehensive, the typical approach of indicating changes from a previous version with change bars are not provided.

The study team at JPL would like to acknowledge the support and help provided by many vendors and personnel from the U.S. Army Corps of Engineers, Yuma Proving Ground, and the U.S. Army Environmental Center. In addition, the study team appreciated the opportunity to have the document distributed to and reviewed by the many participants attending the Golden, Colorado Conference. Conference sponsors provided us the opportunity to have a large user community review the document and provide significant feedback in a most timely manner. In particular we appreciate the support and guidance provided by the following individuals:

Ms. Alicia Allen (U.S. Army Corps of Engineers)
Dr. John Potter (U.S. Army Corps of Engineers)
Mr. Andrew E. Hooper (Yuma Proving Ground)
Ms. Kelly A. Rigano (U.S. Army Environmental Center)

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ABSTRACT

The prospect of using sensor technology for the detection and location of surface and subsurface Ordnance and Explosive Waste (OEW) is assessed to determine its suitability for operations on formerly used defense sites (FUDS). The U.S. Army Corps of Engineers, Huntsville Division, has identified over 900 potential OEW sites, of which as many as 300 may be classified as an imminent hazard. Cleanup of the OEW sites is estimated to cost several billion dollars. However, this cost will increase since the Army is still in the process of identifying contaminated OEW sites. In addition, Department of Defense (DoD) ordnance test ranges, such as the Yuma Proving Ground, contain many types of unexploded ordnance, making the cleanup task more complex. Today, several types of electromagnetic sensors have successfully been used for site characterization. In this report, we have assessed over 30 state-of-the-art and emerging technologies for their applicability to site characterization. This assessment will enable the U.S. Army Corps of Engineers and others to better address the ever-increasing site cleanup problem. Information required to select the appropriate sensors is provided within this document. Over one-hundred sensor technology products and services are surveyed, providing an in-depth summary of technology that can be brought to bear on the OEW problem. In the future, sensor suites and data processing utilizing data fusion should be utilized in less labor-intensive approaches to enhance productivity and increase quality of OEW detection and location. The study team concluded that, although no one sensor type can solve all problems in all FUDS, the U.S. Army Corps of Engineers can use state-of-the-art sensor technologies and adapt already developed DoD sensor data fusion concepts and models to greatly enhance productivity. The probability of success for this approach would be high while the adaptation risk would be quite low because sensor data fusion has traditionally been exploited by the military for similar types of challenging applications. Meanwhile, emerging sensor technologies can be adapted to support sensor data fusion as they evolve.

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* This technology currently employed by the Corps of Engineers

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EXECUTIVE SUMMARY

At the present time there are over 10,000 suspected contaminated sites at more than 2,500 installations currently under Army control and 7,600 former defense installations that have been turned over for civic or private use. The Army has cleanup responsibility at those former sites, regardless of which service used them. A suspected contaminated site can be anything from a motor pool, laundry or landfill, to an abandoned ordnance test site and/or depot facility.

The U.S. Army Corps of Engineers, Huntsville Division, has responsibility for the Ordnance and Explosive Waste (OEW) site cleanup. Potential OEW sites could involve more than 1,000 installations that have already been turned over to the civic or private sector. The OEW contamination presents an imminent hazard to exposed individuals, and therefore the OEW items must be detected and located. OEW examples are bombs, warheads, guided missiles, mortars, small arms, mines, demolition charges, pyrotechnics, propellants, chemical agents, fuzes, boosters, and rocket motors.

The issue of OEW detection and location has been investigated for the U.S. Army Corps of Engineers and Yuma Proving Ground by a study team at the Jet Propulsion Laboratory in Pasadena, California. The objectives of the study were to (1) develop technical tutorials of all relevant sensor technologies; (2) conduct an assessment of current state-of-the-art and emerging sensor technologies for the detection and location of surface and subsurface OEW on hazardous sites; (3) survey sensor technology products and services and provide an indication of technologies that could be brought to bear on the OEW problem.

The vast diversity of ordnance and explosive waste, coupled with the very nature of its designed use in training exercises (e.g., artillery firing, bombing practice), renders the detection and location of OEW a very difficult task. In concentrated target areas such as firing ranges, the scope of the task is less formidable, as the approximate perimeter is relatively well defined. However, in regions of live-fire exercises designed to expose personnel to the experience of live rounds, the impact regions are more diffuse. In addition, a falling artillery round does not always detonate, and it can penetrate the ground by as much as two to three meters. Other OEW concentrations are burial sites, where intentional disposal of obsolete munitions occurred. For example, it was not uncommon for unused munitions nearing expiration of their useful life to be buried in close proximity of the firing range. The disposal of chemical waste by burial is another example. The mustard gas burial site in Manchester, GA, and the Spring Valley burial site near Washington, D.C., are typical cases.

A site that has not been used for some time is subject to vegetation overgrowth, especially in the warmer, wetter climates. The obvious impact on sensor selection is to make the initial detection more difficult by obscuring evidence of ground disturbance, as well as making it difficult to utilize some ground-towed sensors. The influence of the regional geology is a distinctively important factor. Not only will the differences in soil density affect a munition's penetration depth, but the different soil groups will also affect the sensors. Soil with high clay content and a high saline water table will impede the performance of ground-penetrating radar (GPR). Soils of high volcanic content, dark igneous rocks, or large concentrations of iron will impact the performance of magnetometers. The effect of the local climate on the geology can be quite dramatic. Impact scars can remain obvious for years in a dry climate, whereas they are readily and quickly obscured where it is wet.

All of the above factors are further exacerbated by the recent base closures and the resulting urgencies to transfer ownership to the civilian sector. To make matters worse, many of the hazardous sites are in urban areas or are surrounded by population centers. This is the case, for example, with Camp Elliot in San Diego and Johns Hopkins University in Baltimore.

The terrain features of the 31 hazardous sites (listed in Table 3.2.1) evaluated in this study are geologically and environmentally varied: flat, rocky, mountainous, and hills with eroded gullies and other unleveled features. The ground cover varies from none at all to brush and large trees. The soil conditions vary from dry sand to damp gravel and mud; in some areas clay or marl is mixed with dissimilar rock that is often comparable in size and shape to the target ordnance. In order to get a better feel of the 31 hazardous site conditions considered, the representative site characteristics have been summarized in Table E.1. This table illustrates the number of times a site characteristic occurs over the 31 RAC-1 sites listed in Table 3.2.1 (Section 3).

All sensors assessed in this study have both their advantages and disadvantages. For ideal conditions, each sensor would be expected to deliver its ideal performance. Because of the nature of the task of detecting and locating OEW in a real-world environment, there will naturally be impediments to this ideal operation. Some of these impediments will merely result in a loss of performance to a greater or lesser degree, while others are "binary", where the issue is whether the sensor is even capable of performing the function. An example of a binary impediment is a magnetometer's inability to detect non-ferrous objects.

A sensor technology assessment summary is displayed in Table E.2. The table provides the number of sensor types (reviewed within this document) in each of two categories (State-of-the-Art, and Emerging) and the average applicability rating of each sensor type. The results from more detailed sensor classifications (Sections 3.5.1 through 3.5.3) have been averaged and show how well the sensors may perform on the 31 hazardous sites. (Refer to Sections 3.5.1

through 3.5.3 for explanations and caveats regarding using these results for sensor selection. These recommendations are made based upon theoretical strengths of the sensor technologies, not upon individual vendor's implementation of that technology.)

Table E.1. Summary of Representative Site Characteristics

Characteristic	Occurrences
Urban/nearly urban	13
Forested	13
Grassy/chaparral	10
Cleared/sparse	9
Thin clay	18
Thick clay	10
Sandy/loamy	7
Volcanic	3
Flat to gently sloping	23
Hilly/mountainous	9
High saline water table	17
Saltwater coastline	6
Freshwater coastline	4
Wet/marshy	2
Semiarid	7
Soil attenuation 0.7 - 1.3	14
Soil attenuation 1.3 - 3.0	6
Soil attenuation 3.0 - 5.0	9

The term "state-of-the-art" refers to sensor technology solutions that are mature, well-understood, and available off-the-shelf. Technologies that show promise but are still in the research stage are listed as "emerging technologies". A definition of the ranking symbols appears below:

● **Most Applicable** - under the given conditions, these technologies will provide the best performance in their respective areas.

◒ **Average** - this technology will work adequately under the stated conditions, although there are other technologies reviewed herein that will perform the job faster, with greater sensitivity, from greater distances, or with fewer false alarms.

○ **Poor** - under the stated conditions, this technology is not recommended to be used for the detection and location of OEW.

Although each OEW site is different, the technology assessment process is an indication of how universally effective any given sensor might be. As can be seen in the Summary table E.2 (and substantiated throughout Sections 2 and 3), the three highest-ranking classes of technologies for the detection and location of OEW are: highly sensitive or multi-axis magnetometers, airborne ground-penetrating radar, and nuclear activation technology. While other evolving technologies are promising, there is considerable development yet remaining. The most important observation, however, is that no single technology can accomplish this task unambiguously. For all their merits, neither magnetometers, GPR, nor nuclear activation technology applied alone can assure more than a modicum of success probability. While each is a powerful technology with distinct advantages, none has the breadth of capability to interpret all the phenomena that are typically encountered in the search for OEW. This includes the capability to discriminate OEW from background artifacts, the ability to resolve individual entities below ground, and the ability to determine depth below the surface independent of geology.

The study team found that the successful accomplishment of OEW detection and location is dependent upon accurate data collection, sound signal processing methods, and high-level data fusion approaches whereby a discrete suite of sensors is selected and specialized to the requirements of a specific site. Such a suite most likely would consist of at least two of the dominant technologies plus one or two others. The information gleaned from sensor fusion and signal processing would complement each other sufficiently that the vast majority of the OEW at a site can be readily identified for disposal* Implementation of the sensor suite should be motivated by optimizing the sensor characteristics to the site needs, whereas only negligible loss in accuracy would be experienced by using fewer sensors. Any information loss would almost certainly be justified in terms of the savings in cost and logistical expense. This approach must be quantified by assessing the trade-offs based on test site evaluations. The approach must answer questions such as, "If I fly two additional sensors, effectively increasing the cost of the survey, how much will my detection confidence increase?"

In conclusion, to overcome the problems identified in the previous paragraph, the study team strongly recommends the application of sensor data fusion technology be applied to the OEW detection problem. Prior to applying sensor data fusion technology, the techniques should be quantified first by assessing the individual sensor capabilities and performance trade-offs based on actual test site data. This would require the expansion and adaptation of already developed Department of Defense (DoD) sensor data fusion concepts and models. This approach should greatly enhance productivity and increase the quality of OEW detection and location.

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* Source: Gulati, Sandeep and Peterson, John, "Intelligent Electromagnetic Imagery Fusion Server for Unexploded Ordnance Detection and Location", *Proceedings of the Seventh Joint Service Data Fusion Symposium*, Johns Hopkins University, Laurel, MD, October 25-28, 1994

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Table E.2. Sensor Technology Assessment Summary

Sensor Type	# State-of-the-Art Vendors	# Emerging Vendors	Average Applicability Ratings from Tables 3.5.1 through 3.5.3
Proton Precession Magnetometer	3	0	◔
Optically Pumped Magnetometer (*)	6	1	◕
Single-Axis Fluxgate Magnetometer (*)	7	0	◑
3-Axis Fluxgate Magnetometer	0	3	◕
Fiber-Optic Magnetometer	0	2	◕
Overhauser Effect Magnetometer	1	0	◑
SQUID Magnetometer	0	7	●
Electron Tunneling Magnetometer	0	1	◕
Electromagnetic Induction Sensor (*)	3	3	◔
GPR (land-borne) (*)	10	4	◔
GPR (Airborne)	5	6	◑
UWB Synthetic-Aperture GPR (airborne)	0	6	◑
Stepped FM GPR	0	1	◔
Harmonic GPR	0	1	○
Interferometric Impulse Radar	0	1	◔
Cone Penetrometer	3	0	◔
Transient Acoustic Sensor	1	0	○
Seismic	0	0	◔
Ultrasonic	0	0	◔
Acoustic Imaging	0	3	◔
Visible Imaging (*)	2	1	○
Infrared Radiometry (*)	13	0	○
Infrared Imaging Spectrometry	0	1	○
Millimeter Wave Radiometry	1	0	○
2-D LIDAR (*)	2	1	○
3-D LIDAR (LADAR)	0	2	○
Line Spectra LIDAR	0	1	○
Nuclear Technology (non-metallic only)	0	6	◑
Multi-sensor platform	1	3	--
Other Related Technologies	3	3	--

Scale: ○ ◔ ◑ ◕ ●

Poor Average Most Applicable

(*) This technology currently in use by the Corps of Engineers

This sensor fusion capability is now available to support a broad variety of public and private sector purposes in such areas as law enforcement, banking, office automation, traffic control, environmental monitoring, and most certainly OEW recovery. Sensor data fusion has the potential to provide the technology necessary for solving the OEW recovery problem. Data fusion techniques can effectively deal with data errors, data uncertainties, and incomplete data problems often associated with using single sensors.

It is proposed that sensors be evaluated using a known and calibrated test site. After test site calibration and trade-offs have been performed and the results finalized, a specific sensor suite could then be developed and rapidly deployed to real OEW sites for application. The trade-offs involve optimizing the following sensor integration issues based on the needs of each site: 1) Complementary Sensor Integration - integration of sensor data from more than one sensor type to get a global picture; 2) Temporal Sensor Integration - integration over a given time (temporal inferencing); and 3) Spatial Sensor Integration - integration of data over a given space (spatial inferencing).

The study team believes the adaptation of DoD sensor fusion technology would lead to a more definitive and less labor-intensive characterization of the problem. This approach would enhance site characterization productivity and significantly increase the probability of successful detection and location of OEW. Furthermore, because sensor fusion has traditionally been exploited by the military for similar types of challenging applications, the probability of success would be high while the adaptation risk would be quite low.

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Section 1

INTRODUCTION

The U.S. Army Corps of Engineers has extensive Ordnance and Explosive Waste (OEW) site characterizations and cleanup experience. Site cleanup activities include the removal of bombs, warheads, guided missiles, mortars, small arms, mines, demolition charges, pyrotechnics, propellants, chemical agents, fuzes, boosters, and rocket motors. Since 1985, cleanup at about one hundred such sites has been completed or is ongoing. The sites include a former OEW depot at the Spring Valley suburb, Washington D.C.; a former firing range at Martha's Vineyard, Massachusetts; a former impact area at Tierrasanta, California; a former Army Depot at Black Hills, South Dakota, and a former firing range at the shore line of Lake Erie, around Port Clinton, Ohio.

The mandatory center of expertise (MCX) at the Explosive Ordnance Engineering and Design Center, the U.S. Army Corps of Engineers, Huntsville Division, has utilized several types of OEW sensors including magnetometers, electromagnetic (EM) sensors, and ground-penetrating radar (GPR) in these site cleanup operations.

The magnetometers used by the U.S. Army Corps of Engineers are primarily handheld magnetometers and/or gradiometers. For example, the Schonstedt GA-52C handheld magnetometer is a lightweight sensor using fluxgate technology. In operation, this magnetometer is swept across the surface, and an audio signal sounds when ferrous material is proximate. A similar magnetometer, the Mark 26 by Foerster, has also been extensively used for field operations. This unit is larger and heavier than the Schonstedt model, but is also more adaptable to different types of site conditions.

Although these handheld magnetometers are very effective in locating magnetic sources (which may or may not be ordnance), they do have difficulty in some sites. For example, it is very hard to locate metallic objects in a landfill site that is cluttered with metals. In a large area with shrapnel, the extra clutter is so confusing that these handheld magnetometers are not able to positively identify any ordnance.

Electromagnetic sensors such as the Geonics EM31 have been extremely useful in certain sites where most of the ordnance is composed of non-ferrous metals. The EM sensor is an active probe that will induce voltage responses from all types of buried metallic objects.

When using a ground-towed GPR for OEW detection, the penetration depth of the GPR is strongly dependent upon the conductivity of various types of soils, hence the performance of the GPR varies with every site. It generally works well with sandy and dry soil. It has poor penetration depth in clay soil or over sites with a saline high water table. Ample site vegetation not only can attenuate the return signal, but also provide physical impedances to a ground-towed sensor's mobility. Moreover, the lack of advanced processing algorithms to process the GPR data also limits its success rate.

In the future it may be possible for sensor technology to be utilized in less labor-intensive approaches to enhance productivity and increase quality of OEW detection and location. To address this question, we have assessed over 30 state-of-the-art and emerging technologies for their applicabilities to site characterizations to enable the Corps of Engineers and others to better address the ever-increasing site cleanup problem. Information to select the appropriate sensors is provided within this document. Over one hundred sensor technology products and services are surveyed, providing an in-depth summary of technology that can be brought to bear upon the OEW problem.

The following information is provided to assist individuals who are not familiar with the general types of UXO that can be expected to be encountered during a remediation process. The items* and their descriptions are not all inclusive and are not intended to provide a complete inventory of all possible items to be encountered in a FUD site, but rather is intended to provide only a broad overview of potential items to be found in a FUD site. There are actually thousands of different kinds of ordnance that have been used for training on these sites, but when selecting sensor types for detecting UXO, the major factors in general are size, casing material, explosive composition, depth of burial and soil type. The physical characteristics of UXO are illustrated below for those who are unfamiliar with the ordnance types.

Small Arms Ammunition

The projectile is the part of a complete round of gun ammunition that is expelled at high velocity from the gun bore. Samples of complete rounds appear in Figure 1.1. Typical materials are brass and steel. Lengths of their projectiles are on the order of tens of centimeters.

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* Sources for this information:

Jane's Armour and Artillery 3rd Edition 1982-83 Pg. 720-730

Principles of Naval Ordnance and Gunnery, Naval Education And Training Command, NAVEDTRA 10783-C, 1974

Preliminary Warhead Terminal Ballistic Handbook (Pt. 2 - Warhead Terminal Ballistic Performance), Armed Services Technical Information Agency, AD 332 700, 1962 Declassified 1974

Jane's Infantry Weapons 1992-93, 18th Edition, 515-719.

International Defense Equipment Catalogue, 1992-93 Vol. 2

Mine/Countermine Operations, Document FM20-32, Headquarters, Department of the Army Sept. 1992

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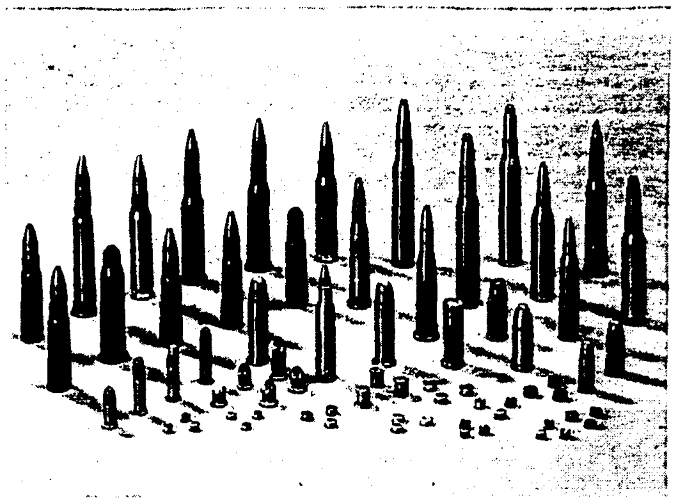


Figure 1.1. Examples of small ammunition.

Rockets

Airborne rockets, consisting of fuzes, warheads, and motors, are combined and assembled in various configurations to meet specific tactical requirements. They are generally 2 to 5 inches in diameter, and about 50 inches in length, including explosive warhead. Explosives within the warhead can be TNT, "Composition B" (a mixture of RDX (cyclonite), TNT (trinitrotoluene), and wax), or "Explosive D" (a phenolic compound). Other warheads deliverable by rockets or howitzers include mines smoke, and nuclear payloads.

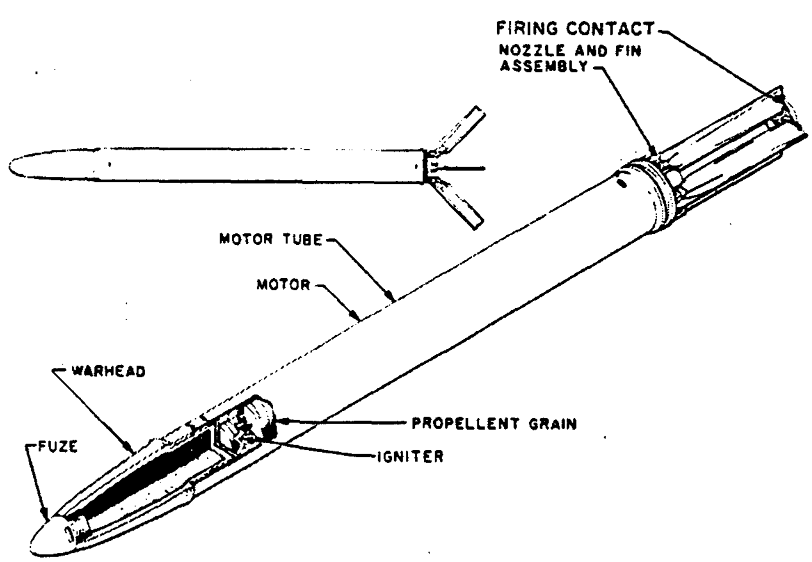
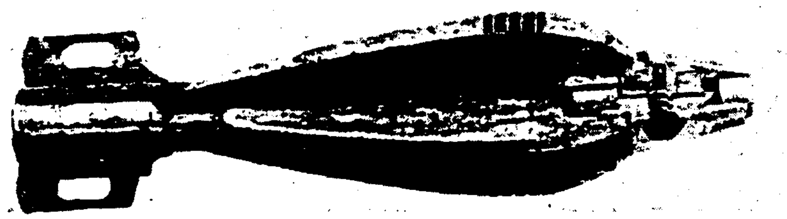


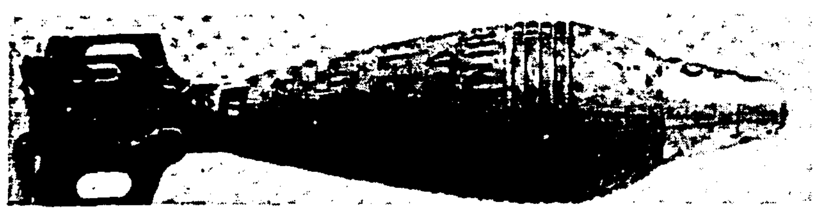
Figure 1.2. Example Drawing of a Rocket

Mortar Ammunition

Mortar ammunition are similar to rockets, except there is no internal propulsion mechanism beyond the initial charge mounted on the tail end. Such ammunition is typically launched by dropping them into a firing tube, called a mortar. When the explosive charge at the tail end hits the tube bottom, the ammunition is propelled in the direction the tube is pointing. From there, inertia takes it to its target, where a second internal charge converts the thick metal casing into flying shrapnel.



M43A1 bomb



81 mm M43A1 HE bomb

Figure 1.3. Example of Mortar Ammunition. Top illustration shows cut-away of detonating mechanism and cavity for explosive.

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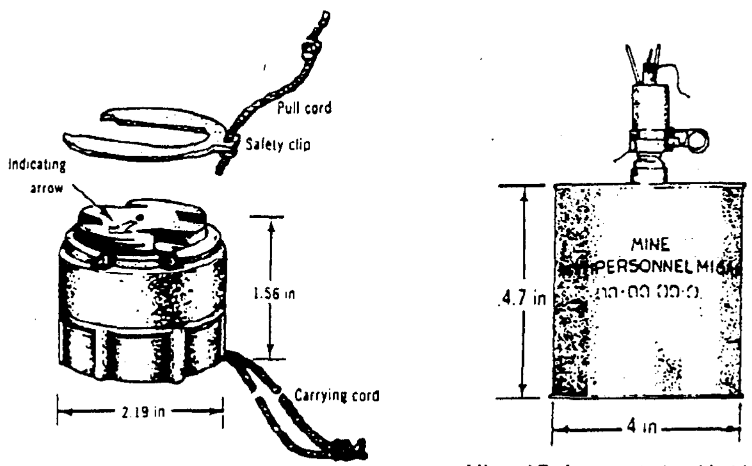
Mines

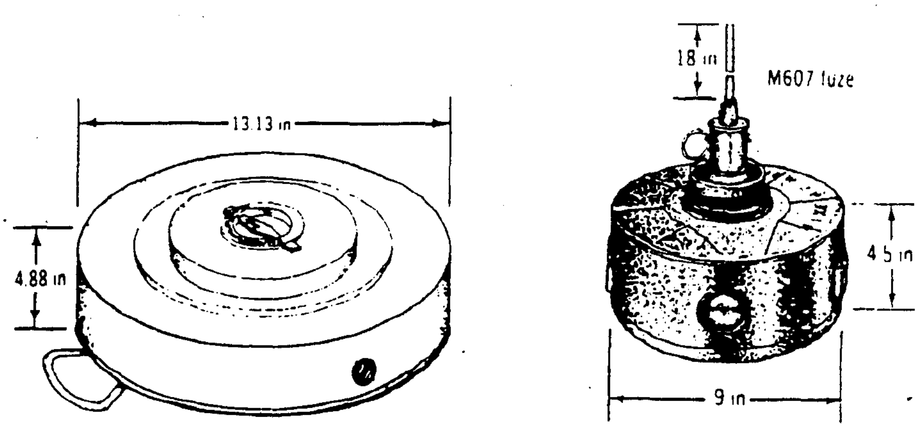
Buried mines come in two general categories: anti-personnel mines (Figure 1.4), which are typically one to three inches in diameter and weigh 1/2 a pound, and anti-tank mines (Figure 1.5), which range from six to twelve inches in diameter, about 3 1/2" thick and a density of 1.5 grams per cubic centimeter. Older mines had an external iron casing and contained TNT as the explosive; newer ones (typically manufactured after 1980) are encased in plastic and employ Composition B as the explosive. These mines are typically buried by hand or via a specialized ground vehicle.



Mine, AP, nonmetallic, blast M14

Mine, AP, fragmentation M16A2

Figure 1.4 Examples Of Anti-Personnel Mines



Mine, AT, HE, heavy, M15

Mine, AT, HE, heavy, M21

Figure 1.5 Examples Of Anti-Tank Mines

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Bombs

Bombs are weapons designed to be dropped upon enemy targets to reduce and neutralize their war potential. A bomb usually consists of a body, stabilizer, and means of detonation. Refer to Figure 1.6 for an illustration of a typical bomb. Bombs can range from 250 lb to 2000 lb in weight, and from 70 inches to 100 inches in length. Explosives used include TNT, Tritonal, HBX (RDX, TNT, plus a stabilizer), and H-6. Fire bombs use a mixture of napalm powder and aviation fuel.

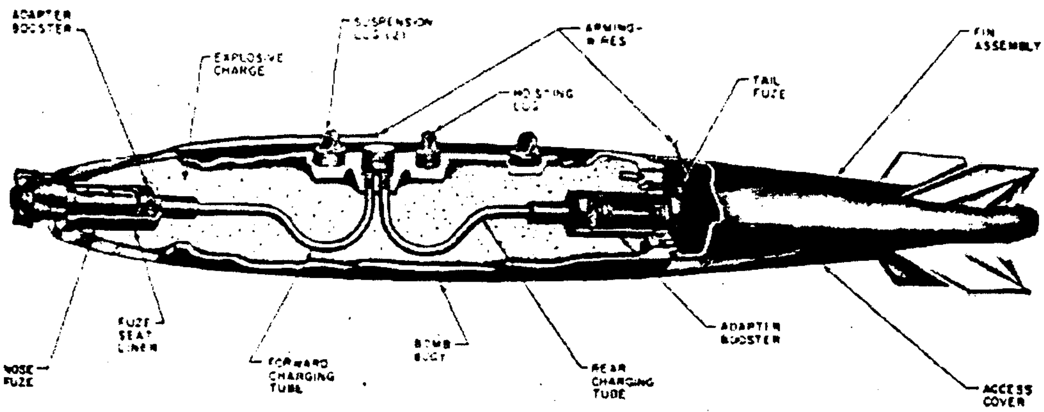

Figure 1.6. Sample Drawing of a Bomb

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Family of Scatterable Mines (FASCAM)

Scatterable mines are designed to be delivered or dispensed remotely by aircraft artillery, missile, or ground dispenser. Typically, a 155 mm ammunition round is filled with 36 small anti-personnel mines, (or about 9 anti-tank mines). The ammunition disperses the mines while still tens or hundreds of feet in the air, and the mines remain on the surface. Typical sizes are five inches in diameter or less for both antipersonnel and antitank mines, (See Figure 1.7 for typical dimensions.) All scatterable mines have a limited active life and self-destruct after their active life has expired, a time period ranging from four hours to 15 days.

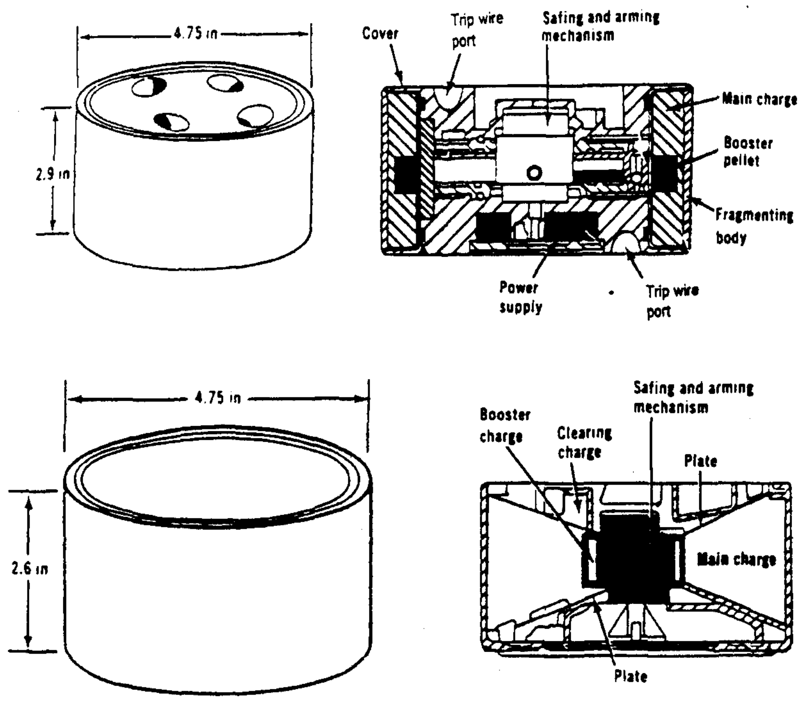

Figure 1.7. Examples of Scatterable Anti-Personnel Mines (top) and Scatterable Anti-Tank Mines (bottom).

Summary of Document

This report is designed to provide the reader with very easy access to information on a specific sensor or combination of sensors whose performance characteristics are well matched to that of the characterization requirements of specific sites. Identifying these sensors and their operational trade-offs is the first step in constructing custom sensor combinations whose data can be fused (combined or merged) to yield enhanced discrimination of the materials of interest. Periodically, as new information becomes available, this document will be updated.

The first-time reader may wish to read this document in its entirety, first absorbing the technical tutorials, which give enough background so as to give meaning to the sensor technology assessment, then moving on to the detailed description of the sensor products survey. The experienced user wishing to obtain information about a particular company, a particular product, a general category, or a general background on any of these may wish to first consult the summary information in Sections 2.4, 4.3, the table of contents, and/or the index.

This document is organized as follows:

Section 1 (this section) provides an introduction and a description of how the document is to be used.

Section 2 contains tutorials on each sensor category, for both state-of-the-art and emerging technologies. They are designed to introduce the reader to these sensor domains, as well as the common industry terminology. The tutorials are presented in increasing level of detail:

Section 2.1: Overview of Ordnance Sensor Technologies
Section 2.2 - State-Of-The-Art Sensor Technologies
Section 2.3 - Emerging Sensor Technologies
Section 2.4 - Summary Of Sensor Technologies

Section 3 strives to assess the sensor technology and demonstrate the sensor selection process for the environmental constraints dictated by a selection of the most urgent RAC 1 (Risk Assessment Code - Priority 1) sites. It also provides descriptions of the hazardous sites considered, including their soil compositions, and provides suggestions as to which sensor technology might best fit the conditions at the site to be cleaned up. Tables summarizing the sensor technology assessment appear at the end of the section.

Section 4 provides detailed descriptions of the currently available sensors using the technologies described in Section 2. Each product description describes capabilities, performance parameters, known limitations, company name, and price. As in the Tutorials section (Section 2), the products described herein are divided into two categories: "State-of-the-Art" that refers to technologies currently available off-the-shelf, and "Emerging Technologies" which are promising technologies that exist in the laboratory or are in the field-proving stage and have not yet been commercially deployed.

Section 4.1 - State-of-the-Art Sensor Technology Products
Section 4.2 - Emerging Sensor Technology Products
Section 4.3 - Sensor Product Summary Tables

Section 5 contains an alphabetical list of vendors mentioned in Section 4, along with a key contact, a telephone number, and the page number where the product is described.

The Appendices consist of a list of acronyms and a glossary (Appendix A), a bibliography (Appendix B), and a detailed definition and breakdown of all soil types throughout the world (Appendix C). Appendix C is used to assist the authors in developing the assessment values for each of the RAC-1 sites considered.

At the end of the document is a form for readers wishing to add or clarify information within this report, and for ordering additional copies.

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Section 2

TUTORIALS

In this section, the basic concepts behind several sensor technologies capable of finding buried. unexploded ordnance are reviewed. Section 2.1 provides an overview of the technologies; Section 2.2 goes into each of these technologies in greater detail, providing necessary details and discussing the characteristic strengths and weaknesses of each sensor category. Section 2.3 discusses emerging technologies, and compares current performance levels with those that are anticipated with these new technologies. Section 2.4 summarizes the information covered in Sections 2.1 - 2.3 in tabular form, showing how the performance of the sensor categories compare against each other. In this document, the discovery of objects is emphasized. Other wastes such as chemical contaminants, while not the primary focus of the document, are addressed in the nuclear techniques and biological sensors sections.

The tutorials are designed to give the reader an understanding of the general approaches, differences, and areas of effectiveness for each of the sensor types outlined in this document. It should not be solely depended upon for sensor selection at a project site; many additional factors need to be considered such as known site activity, available manpower, cost, and a detailed site survey.

2.1. OVERVIEW OF ORDNANCE SENSOR TECHNOLOGIES

This section provides an overview of the 11 classes of over 30 sensor technologies (state-of-the-art and emerging) that are discussed in the remainder of the document. These classes are:

Magnetometers/Gradiometers
Electromagnetic Induction
Ground-Penetrating Radar (GPR)
Visible Imaging
Infrared (IR) Radiometry and Spectrometry
Millimeter Wave (MMW) Radiometry
LIDAR (2- and 3-dimensional)
Nuclear Technology
Cone Penetrometers
Acoustic Sensors
Biological Sensors

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2.1.1. * Magnetometers/Gradiometers

A magnetometer is a device for measuring magnetic fields by utilizing the nonlinear magnetic characteristics of ferromagnetic core material in its sensing element. The terms "saturable-core", "saturable-inductor", "saturated-core reactor", and "peaking strip" have also been used in describing this class of magnetic sensors. It is a directional device, measuring the component of the field parallel to the axis of the sensing coil.

For the detection of OEW, magnetometers are widely used for measuring magnetic fields because of their exceptional price/performance ratio. They have been used in airborne, marine and ground systems in the search for submarines, sunken vessels, archaeological artifacts, unexploded ferrous ordnance, and mines since World War II. Their successful use depends upon several factors, including the nature of the target, the general environment in the target area, the amount of local magnetic disturbance around the target, and the experience level of the operator.

Magnetometers function on the principle that metallic casings of bombs or gun shells contain a ferrous metal such as iron. Ferrous objects cause a perturbation in the natural geomagnetic field (as illustrated in Figure 2.1.1.1) which can be sensed. As buried shells are illuminated by the Earth's uniform primary magnetic field, a secondary magnetic field is induced.

Since buried ferrous metallic ordnance can be detected via this secondary magnetic field it is important to compare the magnitude of the Earth's magnetic field and this secondary magnetic field. By long-standing tradition the unit used to measure the Earth's magnetic field is the gamma, sometimes notated as γ (1 gamma = 10^{-9} Tesla = 10^{-9} Weber/m^2). The Earth's field magnitude ranges from 35,000 gamma at the equator to about 60,000 gamma at the poles. The secondary magnetic field generated by the buried ordnance is proportional to its mass as well as the magnitude of the Earth's magnetic field, and is non-linearly proportional to the inverse of the distance between the ordnance and the measurement instrument. The magnitude of the buried ordnance's secondary magnetic field could vary from a fraction of one gamma to tens of gamma.

To detect ordnance, a magnetometer must be sensitive enough to measure the small secondary magnetic field (e.g., 0.1 gamma) superimposed on a steady background of up to 60,000 gamma. Figure 2.1.1.2 illustrates the measured signal pattern of a buried artillery shell as measured by a ground-towed magnetometer.

* This technology currently employed by the Corps of Engineers

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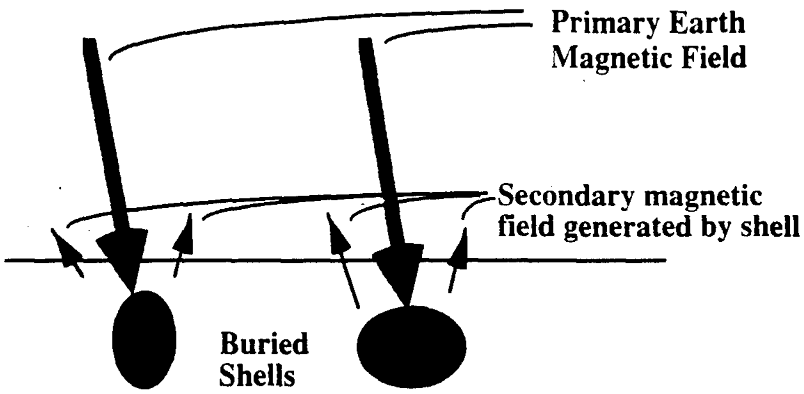

Figure 2.1.1.1 Secondary Magnetic Field Generated by Buried Ferromagnetic Shells

The drawback of a magnetometer is that it requires both a large dynamic range (being able to accurately measure small changes from 60,000 gamma to less than one gamma of ambient field strength) and a high measurement sensitivity such that it can detect the small secondary field in the presence of the Earth's larger magnetic field. Gradiometers have been designed in response to this problem; they have an increased measurement sensitivity in the presence of a large background signal. (See Gradiometers section that follows.)

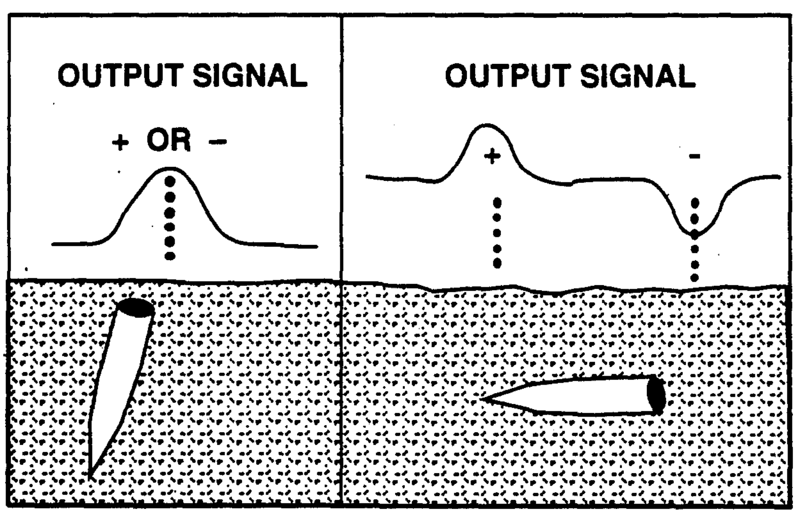

Figure 2.1.1.2 Magnetic Field Signal Pattern of a Buried Ferrous Ordnance

There are six types of state-of-the-art magnetometers and gradiometers: the proton precession magnetometer, fluxgate magnetometer, optically pumped magnetometer, fiber-optic magnetometer, the superconducting quantum interference device (SQUID) magnetometer, and the electron tunneling magnetometer. Details of these magnetometers will be covered in Sections 2.2.1 and 2.3.1.

The choice of sensor for detecting buried ordnance is determined by the size of the anticipated OEW (Ordnance and Explosive Waste), the environment in which it will be sensing, and the strength of the background magnetic field. For example, a soil rich in magnetic material would generate low-level magnetic field perturbations similar to the field perturbations generated from the buried ordnance, making distinction of the sought-after ferrous shell casings difficult. The ratio of the signal strength from the ordnance to that of the ambient fields (Earth's magnetic field plus the field from the clay content of the soil) is referred to as the signal-to-noise ratio (SNR), and is a common quality parameter in the signal measurement world. A low SNR means it is more difficult to discern the secondary magnetic field from the large background field.

Gradiometers

A gradiometer is comprised of a pair of any type of magnetic sensors separated by a distance (typically measured in meters). They can measure the difference or gradient variations of the magnetic moments (i.e., the product of magnetic field volume and magnetic field intensity) caused by the low-intensity secondary magnetic field. Their sensitivities are much higher than that of any single magnetometer, resulting in more than a four times increase in sensing range. State-of-the-art gradiometers usually can measure three axes, making it possible to measure vector magnetic fields in the x, y, and z directions.

The basic structure of a gradiometer is illustrated in Figure 2.1.1.3. A handheld gradiometer contains two magnetometers, A and B, separated by a distance *d*. Since the secondary magnetic field generated by a buried ordnance varies with the distance between the object and the sensor, the magnetic fields measured by sensors A and B are different. A signal proportional to the ratio between the different magnetic field intensities between sensor A and B could thus be measured wherever a buried ferrous object is present.

Sales representatives often refer to the terms "continuous wave", "total field", and "transient wave" when discussing their magnetic sensing products, even though these terms are not commonly used in scientific circles. (The word "wave" is also inappropriate when discussing magnetism.) Below is a synopsis of what is probably meant by these terms:

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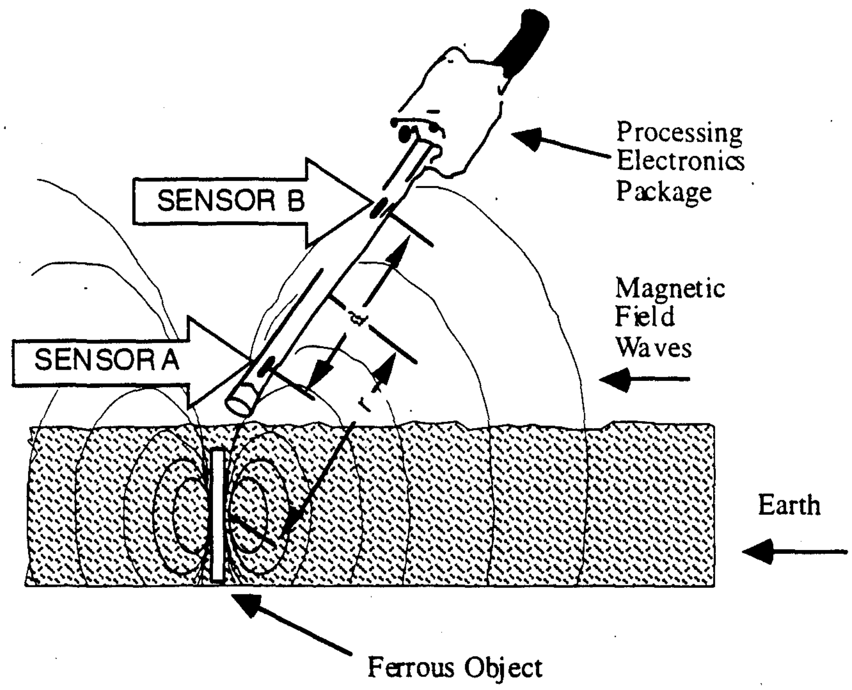

Figure 2.1.1.3 Simple Hand-Held Gradiometer

Continuous Field — This refers to the primary and secondary magnetic fields that can be sensed by a standard fluxgate magnetometer. In most cases the Earth's ambient magnetic field (primary field) is significantly stronger than the field from the local object (secondary field); most standard magnetometers have neither the dynamic range, sensitivity, nor stability necessary to strongly identify the local object.

Transient Field — This refers to the rapidly-changing field differences that can be sensed by gradiometers. A background magnetic field common to both sensors is rejected, leaving only the (transient) difference as generated by the local object.

Total Field — This term means a combination of both continuous field and transient field; sensors adept at sensing total fields have a wide dynamic range and are sensitive and stable enough to positively sense the effects of a local object (1 gamma) in the presence of a large ambient field (50,000 gamma). Optically pumped magnetometers are a good example of a total field sensor.

Although magnetometers and gradiometers are extremely useful in buried ordnance detection, they are limited to detecting only ferrous objects. Their effective working distances are different as well; where the measurable field strength (F) for a magnetometer decreases by the equation $F=1/r^3$, for a gradiometer the strength decreases more rapidly, by the equation $F=1/r^4$, r being the distance between the sensors and the object. This is why gradiometers are not considered ideal for detecting deeper targets.

2.1.2. * Electromagnetic Induction

Electromagnetic induction sensors can be used for both ferrous and non-ferrous metallic ordnance detection. A common example of such a sensor is the inductive metal detectors used to locate buried metallic pipes or coins buried in beach sand. This detector works on the principle that the presence of a nearby metal causes a change in the inductance of a coil. The change in inductance causes a corresponding change in the resonance frequency of a tuned circuit. This change in frequency, indicating the presence of the object, can be detected by an operator.

A vehicle-towed detector system utilizing this technology was recently designed, built, and tested for the detection of unexploded ordnance. The detector component of the system consisted of two adjacent electromagnetic induction sensors, each of which received input from a coaxial, co-planar pair of square transmit and receive coils. In a sensor of this type, a pulse current is passed through the transmitter coil, generating a magnetic field, which penetrates the soil and illuminates the buried metal object. This magnetic field generates eddy currents in the metal object, which in turn induces a voltage in the receiver coil.

Figure 2.1.2.1 depicts the general arrangement of the transmit and two receive coils for measurement of object depth and signal profiles. The detected voltage waveform illustrated in Figure 2.1.2.2 indicates the presence of a metallic object. This electromagnetic induction is more versatile than the magnetometer and gradiometer because it is able to detect all types of buried metallic objects.

The electromagnetic induction system can be used for the detection of individual ordnance pieces buried in shallow soil, although in the real world these ideal conditions do not always exist. Using ground-towed EM sensors to locate shallow ordnance on some sites may be unsafe, as the EM waves may detonate

* This technology currently employed by the Corps of Engineers

the UXO. For more deeply buried ordnance, this system lacks the spatial resolution necessary for shape and size identification.

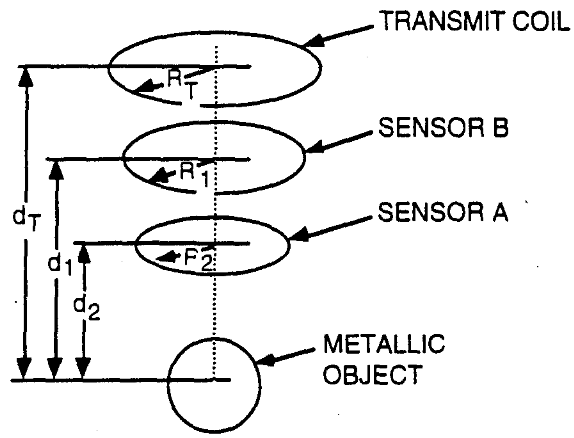

Figure 2.1.2.1 Electromagnetic inductor sensor geometry

To detect deeply buried ordnance with better 3-dimensional shape and size resolution, radar technology needs to be explored.

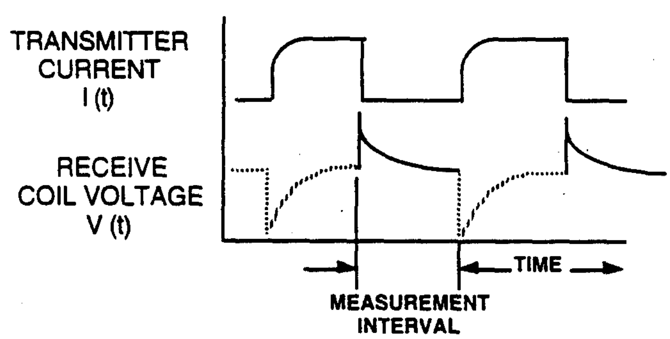

Figure 2.1.2.2 Idealized transmitter current and receiver voltage sensor signal waveforms

2.1.3. * Ground-Penetrating Radar (GPR)

Radar (radio detection and ranging), as well as the electromagnetic sensors described in the previous section, is an active remote sensing system because it

* This technology currently employed by the Corps of Engineers

provides its own source of energy. The system "illuminates" the terrain with electromagnetic energy, detects the energy returning from the terrain (called radar return), and then records it as an image. (Passive remote sensing systems such as photography and thermal infrared sensing detect the available energy reflected or radiated from the terrain, whereas radar systems operate independently of lighting conditions and largely independent of weather.)

Radar operates in the radio and microwave bands, typically ranging from a meter to a few millimeters in wavelength (about 100 MHz to over three gigahertz in frequency). In ground-towed systems, the transmit and receive sensors generally point downward; this configuration is known as "vertical profiling mode". Airborne radar can use vertical profiling as well as side-looking mode (which means aiming the transmitting and receiving antenna(s) toward the port or starboard of the airborne craft).

Two basic radar systems have been widely used for various applications: real-aperture radar and synthetic-aperture radar (SAR). The difference between these two systems is that synthetic-aperture radar uses extensive processing to increase the effective size of the antenna. This results in higher resolution in the azimuth (or the along-track) direction. Since the resolution of the radar image is proportional to the radar antenna aperture size, the real-aperture system uses an antenna of the maximum practical length to produce a narrow angular beam width in the azimuth direction. The synthetic-aperture radar employs a small antenna that transmits a relatively broad beam. The Doppler principle and special data-processing techniques are employed to synthesize the azimuth resolution of a very narrow beam, the same as that produced by a very large aperture antenna, resulting in very-high-resolution radar images. The SAR data requires very sophisticated post-processing algorithms to obtain the final image.

Although the majority of radar applications involve propagation through the atmosphere, such as those in various air- and spaceborne image radars, it has been known for some time that radar can also be used to detect subterranean objects. By using appropriate waveforms, antennas, and signal processing, one can obtain remarkably informative data regarding buried objects and geophysical features.

The ground-penetrating radar technique is similar in principle to acoustic and seismic techniques. (See Sections 2.1.10, 2.2.8, and 2.3.9 for details on acoustic and seismic technologies.) The radar produces a short pulse of high-frequency electromagnetic energy (100 - 3000 MHz), which is transmitted into the ground. This transmitted signal travels in the ground with the reflected signals traveling back to the antenna and then to the receiver. The propagation of the radar signal depends on the high-frequency electrical properties of the ground.

In the design of a ground-penetrating radar, the radar operating frequency is the most critical factor. In general, a low-frequency radar is more desirable for its better penetrating capability† . But, a lower frequency radar has inherently lower resolution, since it is bounded by one quarter the wavelength* . For a resolution of 2 meters, the lowest frequency one can use is about 37.5 MHz. At GPR frequencies, radar waves are able to penetrate both water and soil and therefore could be utilized for both land and water ordnance and explosive waste (OEW) detection. New GPR technologies such as frequency modulated continuous wave (FM-CW) sweep through a range of frequencies in order to obtain the best of both worlds: greater depth penetration and higher resolution of the near-surface objects.

The second most critical factor is the radar bandwidth. In general, the wider the bandwidth, the better the range resolution. However, this may not be true for a ground-penetrating radar since the higher frequency component may not be able to reach the underground object to obtain its backscatter (reflection). Typical a wideband GPR unit has a bandwidth-to-center-frequency ratio of one; that is, a 100 MHz impulse radar would have a bandwidth of 100 MHz stretching from 50 to 150 MHz typically. In addition, within the commonly used frequency range of 10 MHz to 2000 MHz, some of the bandwidth falls within the television and FM radio transmission bands. Therefore, interference with or from TV and FM signals can be a significant problem.

The equipment used in all GPR systems consists of four main elements: the transmitter unit, the receiving unit, the control unit, and the display/recorder unit. Figure 2.1.3.1 shows a simple block diagram of a GPR system. A number of variations to this system are possible that make it more practical for different applications. Many systems, for example, employ two separate antennas rather than multiplexing a single antenna as shown in Figure 2.1.3.1. Also, when airborne, the electronics must compensate for the displacement of the reflected signal caused by aircraft motion.

The depth of penetration of a GPR is determined primarily by the attenuation produced by the sum of electrical conductivity, dielectric relaxation, and geometric scattering losses of the ground. Depth of penetration can range from hundreds of meters in low electrical conductivity soils to tens of meters in granite to a fraction of a meter in high-clay-content soil. The center frequency of the radar system dictates the amount of clutter and scatter which may inhibit detection of targets at deeper depths while the conductivity controls the exponential attenuation of the signals as they propagate through the ground. Fresh water attenuates substantially less than salt water, which makes GPR better suited for rivers and fresh-water lakes than oceans. Temperature of the soil matters as well; in theory a GPR can penetrate frozen ground as easily as it

† In many circles, the term "low-frequency radar" and "GPR" are synonymous.

* Many estimate the resolution to be one third the wavelength in the ground for raw data, and one eighth the wavelength in the ground for processed data.

0 1 1 3 6 7

can dry sand. (The ground must be thoroughly frozen for this benefit, however. See Section 2.2.3.1 for more details.)

There is also a derivative of GPR called harmonic radar. Harmonic radar operates on the principle that, when probed by a standard radar pulse, only manmade objects with sharp edges will respond with a reflection of roughly three times the probing frequency (also called the third harmonic). This inherent selectivity reportedly makes it very easy to differentiate between buried rocks and ordnance and explosive waste (OEW). See Section 2.3.3.1 for more detail on harmonic radar.

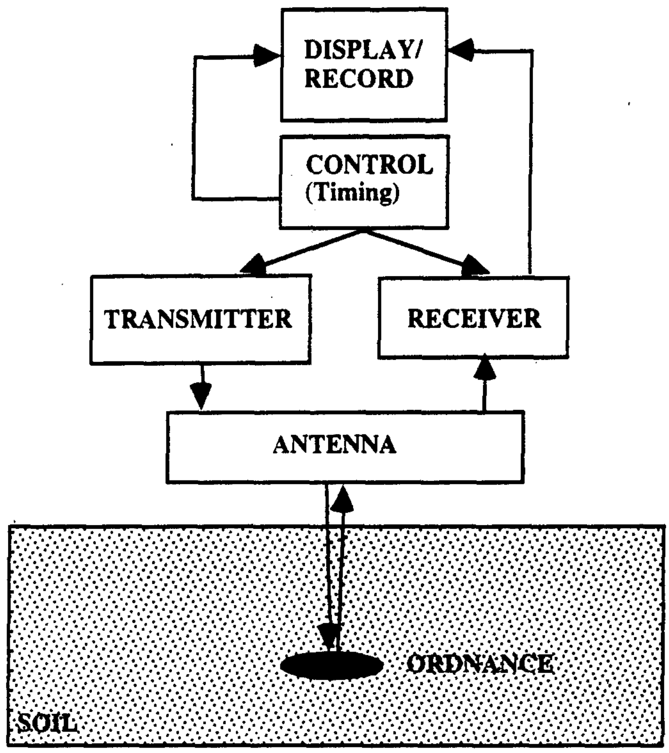

Figure 2.1.3.1 Block diagram of a typical GPR system

2.1.4. * Visible Imaging

Visible imaging, as the name implies, refers to the capturing of visible light using a camera. The technique is useful for detecting surface OEW on flat, empty land, but not very useful in areas with an excessive amount of visual clutter such as foliage and rocks. Visible imaging tools are valuable when combined with other sensor types (such as ground-penetrating radar or infrared sensors)

* This technology currently employed by the Corps of Engineers

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to help identify and de-clutter extraneous findings collected from the other sensors.

Conventional photographic film could be used for a site survey, but capturing the image in electronic form lends itself better to automated data fusion and reduction. The best device for electronic photography is the charge-coupled device or CCD, which can also be found in all of today's consumer video cameras. CCDs are small, lightweight, and require little power relative to their electronic imaging predecessors. Specialized versions exist possessing both high resolution and wide spectral sensitivity.

Visible imaging has the same limitations as human vision for detecting surface OEW: It is less effective in poor lighting conditions, cannot easily distinguish objects when surrounded by objects of similar texture and color, and is useless in fog or cloudy situations.

2.1.5. * Infrared (IR) Radiometry and Spectrometry

Infrared (IR) Radiometry is the technique of identifying objects by measuring their thermal energy signature in the IR spectrum as shown in Figure 2.1.5.1.

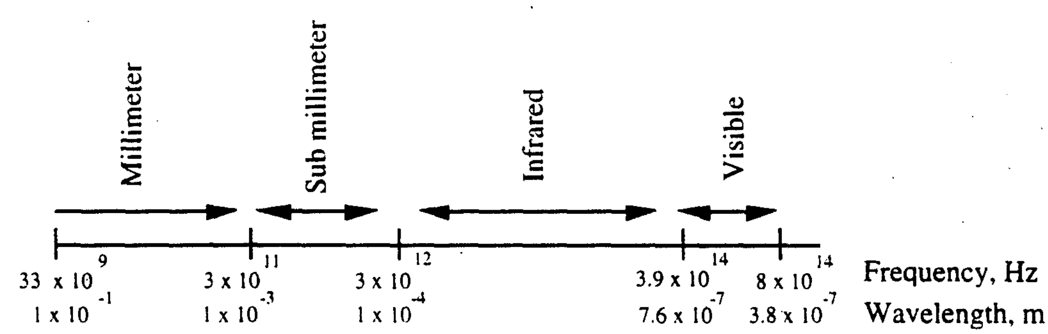

Figure 2.1.5.1. Electromagnetic Spectrum

Ordnance, weather exposed on the surface or buried underground, possesses a different heat capacity as compared to its surrounding soil. (Metallic OEW is heated to a higher temperature than its surrounding soil when the ordnance is illuminated by the sun.) The temperature difference will result in different photon emittance by the soil and the ordnance. These photons are detected and differentiated by an imaging IR detector array. Thus, the approach of using infrared sensors will enable the detection and identification of the location of the OEW.

* This technology currently employed by the Corps of Engineers

However, successful ordnance detection using this approach depends on adequate OEW-to-background contrast. Therefore, weather conditions, time of day, background environment, size and composition of the ordnance are major factors in achieving a good ordnance-to-background contrast.

The OEW-to-background contrast can be improved by using IR spectrometry, which will be described in detail in Section 2.3.5. IR Spectrometry adds high spectral resolution to the process, thus, allowing finer discrimination of substances.

In Section 2.2.5, the physical principle of IR radiometry will be introduced, and available IR sensing technologies described. Also, examples of OEW detection using the IR technologies are provided.

2.1.6. Millimeter Wave (MMW) Radiometry

Millimeter wave radiometry (MMW) works on the same principle as infrared (IR) imaging: a foreign object in an otherwise homogeneous surrounding will exhibit a difference of temperature from its surrounding, detectable by monitoring either the infrared or millimeter wave regions of the electromagnetic spectrum (refer to Figure 2.1.5.1 to find where this band occurs. The MMW region is roughly three orders of magnitude lower in frequency than the IR band).

MMW emissions are in a lower frequency band than IR and are generally weaker than the IR emissions for a given object. Although weaker, they can be used in damp weather, which normally absorbs infrared radiation but does not attenuate MMW frequencies. One disadvantage of MMW technology is its long data collection and processing time; in most cases it can take over a minute to construct a single image, although new technology is continually reducing this value.

2.1.7. * LIDAR

LIDAR is the acronym for LIght Detection And Ranging, which is the analog of RADAR (RAdio Detection And Ranging) operating generally in the visible and infrared bands of electromagnetic radiation. The principles are identical: a pulse of coherent radiation is transmitted and at the same time a timer is started. When the pulse strikes anything that reflects or backscatters energy, the signal is returned to a receiver at the same location as the transmitter (monostatic) or at another location (bistatic) and the timer is stopped. Since both light and radio waves travel at the speed of propagation of electromagnetic radiation (c = 3 x

* This technology currently employed by the Corps of Engineers

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10^8 meters / second), the elapsed time, t, between the transmitted pulse and the return is proportional to the distance or range (R) to the target.

$$R = 2c/t$$

An alternative implementation of the receiving technique is to turn the receiver on at the time when a return from a known object is expected. This is known as range gating and can improve the signal-to-noise ratio (SNR) by preventing the receiver from integrating noise until the signal arrives. If the receiving equipment is comprised of an array of detectors (a required configuration for imaging), the received signal can be angularly resolved as an image of the object from which the return signal was reflected. Again, time or range gating can be used to enhance SNR. This technique is referred to as imaging (2-D) LIDAR. If the receiving imager is gated on at discrete intervals after transmission of the initial pulse, then the image received at each interval is a "picture" of the view of the LIDAR at the equivalent distance. The resulting collection of images can be reconstructed to represent a three-dimensional (3-D) picture of the space examined out to a range limit determined by the attenuation of the transmitting medium (atmosphere) and the detection threshold or sensitivity of the receiver.

LIDAR sensors are generally used on airborne platforms, although some systems are adaptable to surface ships and submerged vehicles as well. Ranging limits are determined by sensitivity of the receiver and by the signal's ability to transmit through the medium. The medium is generally water or the atmosphere, as LIDAR does not perform ground penetration. Examples of poor transmission abilities affecting image quality include heavy rain, fog, and highly turbid lake or surf zones.

2.1.8. Nuclear Technology

Nuclear technology is a technique currently employed in airports for close-proximity explosive detection. This technique exploits the fact that certain chemicals found in explosive compounds (such as nitrogen , hydrogen , and oxygen) respond in a unique way when exposed to radiation. For example, nitrogen gives off gamma radiation with a unique energy when exposed to low-energy neutrons.

There are four types of nuclear technology employed for explosive detection: 1) electron-beam X-ray activation, 2) thermal neutron analysis, 3) neutron thermalization gauge and 4) fast neutron activation. The biggest difference between the first and the second and third is the source of the radiation. Thermal neutron analysis and neutron thermalization gauge excites the nitrogen in an explosive by generating neutrons from radioisotopes such as Californium-252, rather than using X-rays. The fourth technique, fast neutron analysis, reduces the incidence of false positive results by also looking for telling

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amounts of oxygen and carbon, two additional elements commonly found in explosives. All techniques make distinctions between the slower-traveling neutrons (which almost all materials absorb), and the higher-speed neutrons, which interact with nitrogen, hydrogen and oxygen.

Non-metallic land mines are difficult to detect using magnetometers, but thermal neutron analysis can be employed to address this problem.

2.1.9. Cone Penetrometers

Cone penetrometers are long rods, with a hardened cone tip, that are pushed deep into the ground via a mechanism on a heavy truck. Electronic sensors in the cone tip relay data back to the surface. This information is collected and viewed onboard the truck, or held for later processing. Cone penetrometers have not been deployed for the purpose of detecting buried ordnance due to the possible danger of setting off the OEW during cone insertion thrusts into the ground, which typically measure 10,000 pounds.

Sensors contained in the cone tip can obtain data on subsurface pressure, resistivity, or water/soil analysis. Other tip devices generate and receive electromagnetic waves, or measure seismic waves. Timing and intensity of these received or reflected waves indicate the density (and vector directions of) the surrounding soil. Older, entirely mechanical penetrometers exist, but most cone penetrometers today are electronic.

Equipment usually consists of a standard rod to which various probe tips are attached, depending on the desired measurement. Data may be processed to provide limited geologic horizontal or vertical profiling of an area. Cone penetrometers are presently being used for subsurface environmental or geological site characterization and sampling, particularly in relatively hard or soft soils. A combination of probing techniques may be used one day to locate subsurface ordnance.

Cone penetrometers are available as either transportable or portable devices. The transportable version requires a large truck to carry the cone penetrometer. Figure 2.1.9.1 shows an example cone penetrometer truck in operation. These trucks utilize a removable ballast as a main part of the reaction mass to permit efficient relocation, operation on soft sites, and high push capacity when needed. A truck's push capacity may range from 36,000 pounds (18 tons) to 66,000 pounds (33 tons) depending upon the ballast.

A portable high capacity penetrometer (as shown in Figure 2.1.9.2) is highly versatile. When properly secured by a clamping system, it has the structural capacity to push the probe into cemented soils and soft rocks with over 100,000 pounds of thrust. Impenetrable layers are cored with a drill which is

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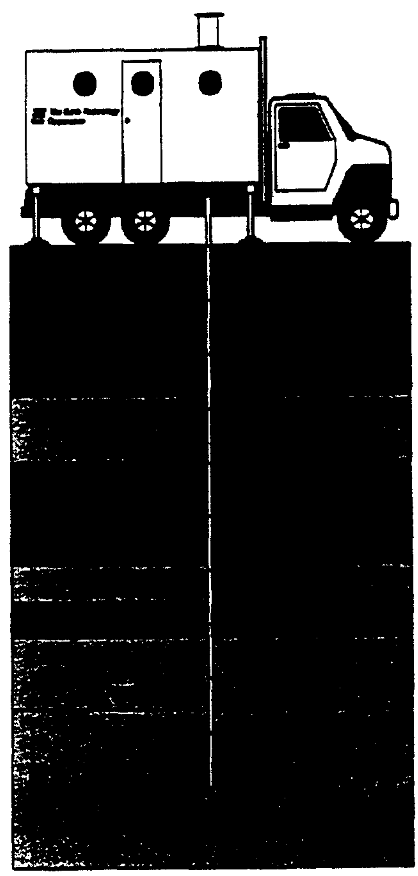
attached directly to the penetrometer frame. The frame width is less than four feet wide so that the system can be used in most places. The entire transportable cone penetrometer unit can be moved from one location to another via a trailer as shown in Figure 2.1.9.3.

Specialty probes which incorporate other technologies such as a gamma radiation probe for radiation contaminant identification are now available. Current research includes magnetometer, LIDAR and other ground penetrating radar capabilities housed within a probe itself. However, as products of this nature are still under development, no data is available regarding their applicability to locating OEW.

The cone penetrometer is not recommended for the location of buried ordnance, since the penetrometer probe might accidentally detonate the UXO it is trying to detect (while pushing the rod into the earth). They are not better at detecting OEW than other sensors described in this document; they cannot distinguish between a rock and UXO, and their probing range from each penetrometer hole is limited.



Source: Earth Technology Corp.

Figure 2.1.9.1 Example of Cone Penetrometer Operation

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The cone penetrometer's poor match for OEW detection was not discovered by the study team until research into method and vendors was well under way. Rather than remove the information already collected, the section describing cone penetrometer vendors (Section 4.1.4) was left as-is and no attempt to complete the exhaustive list was made.

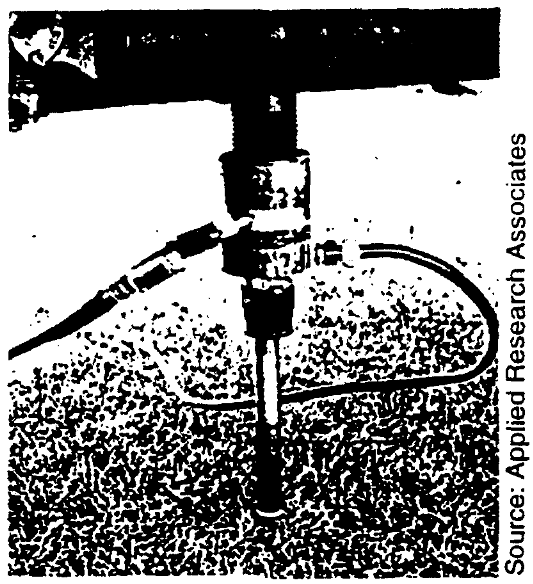

Figure 2.1.9.2 A Portable High Capacity Penetrometer.

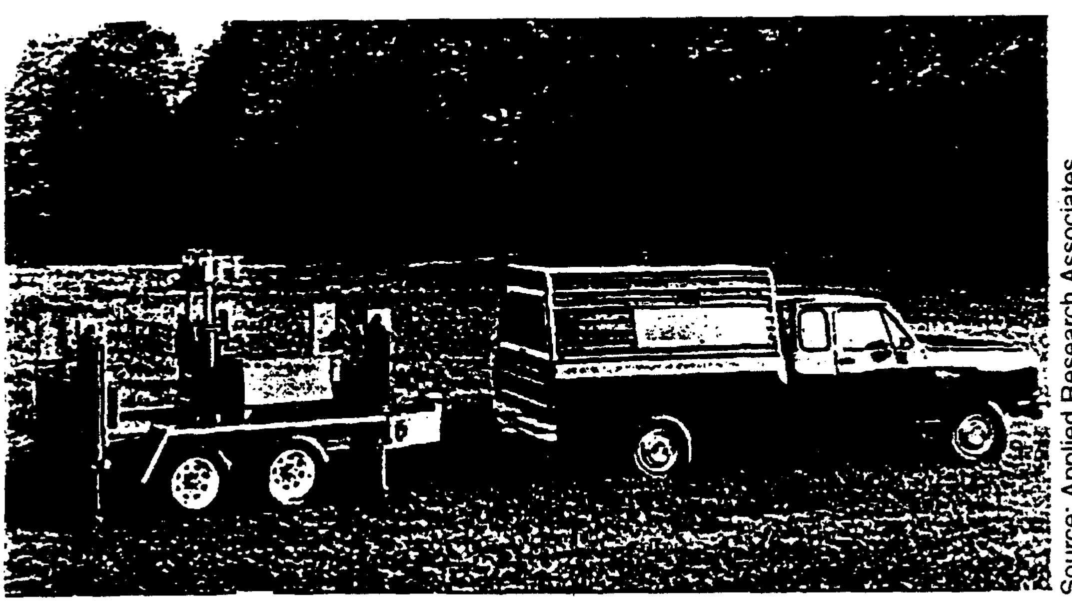

Figure 2.1.9.3 Trailer-Mounted High Capacity Penetrometer for ease of Relocation.

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2.1.10. Acoustic Sensors

Acoustic energy or sound propagates as waves. In contrast to light, which can travel through empty space, sound waves require some kind of elastic matter for their propagation. The propagation medium can be a gas, such as air; a liquid, such as water; or a solid, such as soil.

The speed of sound is determined by the pressure, temperature, and other properties of the material through which it travels. The speed of sound in air, at a temperature of 20° C and at normal atmospheric pressure, is 1,125 feet (343 meters) per second as shown in Table 2.1.10.1. Thus, a sound wave requires almost one second to traverse a distance of 1,000 feet (305 meters). A light wave travels the same distance in less than a millionth of a second. It is because of this large difference between the velocities of sound and light that we hear thunder after we see the lightning.

Table 2.1.10.1. Velocity of Sound Through Various Media

Medium (20 °C)	Velocity of Sound (m/sec)	Velocity of Sound (ft/sec)
Air	343	1,125
Water	1,498	4,915
Sea water	1,531	5,023
Lucite plastic	2,680	8,793
Steel	5,060	16,600
Aluminum	5,100	16,700
Pyrex glass	5,640	18,500

The velocity of sound in liquids and solids usually is considerably greater than in gases. This is so because the atoms and molecules in liquids and solids are much closer to each other than in gases, and the forces between them are much greater. At 20° C, the velocity of sound in pure water is 4,915 feet (1,498 meters) per second.

2.1.10.1. Basic Acoustic Systems

In order to detect and locate an object, the basic acoustic system will generate the proper acoustic frequency which propagates through a medium. These acoustic signals will bounce off or echo back from any object. The amount of reflection is the same regardless of whether it is a rock or ordnance because a reflection is caused by a sudden change in the density of the medium in which the acoustic wave is traveling. Based on the reflection of the returning waves, the object is mapped as an odd-shaped object using imaging which is the optimal scheme to distinguish between a rock or ordnance.

2.1.10.2. Various Types of Sound Ranging

There are three types of sound ranging techniques: seismic waves, ultrasonic waves, and transient wave. Seismic and ultrasonic waves, which can be applied to the detection and location of OEW, will be discussed in detail in section 2.3. Transient wave will not be examined further because it cannot be considered as a viable solution for the detection and location of ordnance. The following example explains why:

If an impulsive sound wave from a distant source like a gun is received by at least three microphones placed at precisely known intervals along a line (more than three are used in practice), knowledge of the sound velocity in air and the differences in time of arrival of the sound signal at the various microphones is sufficient to yield the bearing of the source and its distance from the microphone range. This is the basis for sound ranging in air, known as transient wave. There are, to be sure, many complicating factors, such as the variation of sound velocity due to temperature gradients and wind velocity. Meteorological measurements are always important in sound ranging in air. The object in question must also be the noise source (uncharacteristic of OEW) and it must be airborne, hence, the use of transient wave to detect and locate OEW is not possible.

2.1.11. Biological Sensors

Animals have long been employed for military purposes. Dogs, noted for their acute sense of smell, provide a quick and effective method for OEW detection. Explosive munitions in or out of shell cases (including plastic explosives) continuously give off vapors. Trained dogs may be used to locate mines by smell. In fact, their ability to do so exceeds that of electronic detectors, including those based on odor sensing.

The dogs undergo a six-month training period. They are routinely trained to detect mines buried up to six inches below ground, while remaining ten feet away. Under ideal circumstances, detections can be made from a distance of 200 feet; under worst circumstances, within two feet.

Dogs may be used on or off-leash. However, when equipped with a transmitter the dog may work up to 300 feet in front of the handler, frequently out of visual contact. This provides an advantage in forested or rough terrain, or in urban areas. Another advantage exists in the dog's ability to combine visual cues with sense of smell to respond to metal or plastic casings, and other components, as well as to the trip wires used to set off some mines. An advantage over metal detectors is in their ability to detect explosive filler, regardless of casing material.

A disadvantage is a short time period for which this method remains effective. As placed explosives age, they give off decreasing amounts of odor. In testing, OEW aged up to sixteen months seriously impaired the dog's ability to detect it, as it would the ability of electronic odor detectors.

Because the scope of this report is to evaluate manmade sensor technologies, the use of canines (and other pheromone-sensitive animals such as pigs and rats) will not be included in the product summaries or comparisons.

2.2. STATE-OF-THE-ART SENSOR TECHNOLOGIES

The term "state-of-the-art" refers to mature, well-understood technologies that are currently available off-the-shelf and can be readily deployed. Section 2.3 describes "emerging sensor technologies" that are promising technologies still in the development or research (or paper study) stages.

This section presents a more detailed explanation of the general introductions provided in Section 2.1. Some of the mathematics behind the main sensor technologies and specific trade-offs of the techniques are provided.

2.2.1. * Magnetometers

Magnetic sensors comprise an important class of scientific instruments with areas of investigation and use ranging from commercial to basic research to military deployment. For the measurement of low-frequency magnetic fields at levels below 10^{-9} Tesla (1 gamma), several distinct technologies have been developed:

(1) proton precession devices
(2) optically pumped devices
(3) fluxgates
(4) superconducting quantum interference devices (SQUIDs)

2.2.1.1. Proton Precession Magnetometer.

A proton precession magnetometer is based on the principle that magnetic fields could be inferred by measuring the movement of free precession of protons in a liquid sample that contains an unbalanced polar molecule (such as water, kerosene, or other hydrocarbon fluids). Normally these protons freely oscillate at a natural frequency, called the Larmor frequency. When polarized and subjected to an ambient magnetic field, however, the frequency of precession will deviate from the Larmor frequency in proportion to the strength of the ambient field. This type of magnetometer provides a new, absolute standard for magnetic field measurements that is more reliable than other conventional devices, such as the single-axis fluxgate magnetometer (described in Section 2.2.1.3.)

In operation, a strong direct current (DC) magnetic field pulse is applied to the liquid sample, causing the dipole-like protons to align themselves with this field, as illustrated in Figures 2.2.1.1 and 2.2.1.2. When the pulse is switched off, the protons—along with neighboring molecules—oscillate or "precess" like a miniature gyroscope about the ambient magnetic field (such as the Earth's

* This technology currently employed by the Corps of Engineers

magnetic field). The deviance from the natural Larmor frequency of this precession is precisely proportional to the strength of the ambient magnetic field. The protons' precessions generate a small voltage that can be detected in the same coil that was used to apply the pulsed magnetic field. Magnetic fields are typically measured in nano-Teslas (nT), which is also referred to as gamma (γ). One nT = 1 gamma = 10^{-9} Webers/m^2.

The advantage of this method is it measures absolute magnetic field intensity and does not suffer any form of drift. It is also immune to external variables such as orientation, temperature, or lack of a reference field of known strength.

The two major disadvantages of the proton precession magnetometer are: (1) susceptibility to noise, particularly from nearby AC power sources or transmission lines and electric storm activity; and (2) susceptibility to a field gradient in the sample volume.

The sensitivity of this magnetometer is dependent upon the sampling rate. Usually longer sampling time (i.e., integration time) will result in higher sensitivity. A state-of-the-art system can achieve a sensitivity of 0.05 gamma in a 1-second sampling time. A sensitivity of 0.5 gamma can be achieved with a 0.1-second sampling time.

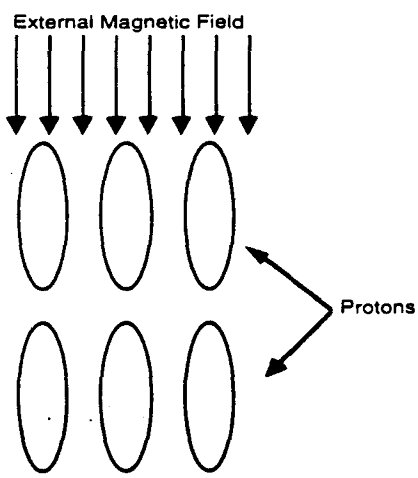

Figure 2.2.1.1. Protons in a liquid sample align along an external magnetic field.

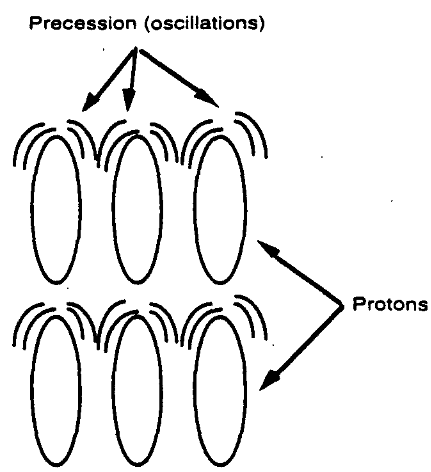

Figure 2.2.1.2. Protons precess after extern- field is removed, producing a measurable voltage in proportion to the ambient magnetic field.

2.2.1.2. * Optically Pumped Atomic Magnetometer.

The principle of operation of an optically pumped atomic magnetometer is similar to that of the proton precession magnetometer. In the atomic magnetometer, the proton is replaced by an atom of a specific gas vapor. An external circularity-polarized illumination (pumping) light source excites the atom from its ground state to multiple levels of excited states. This process of optical alignment corresponds to the polarized condition of the proton precession magnetometer. Having been aligned in this way, atoms precess about an ambient magnetic field at the appropriate Larmor frequency; the natural resonance frequency determined by the atomic structure. For example, in a potassium-based optically pumped magnetometer, the output of the sensor is a Larmor frequency of the potassium valence electron proportional to the measured magnetic field, at about 7 Hz per nT. If the measured field increases by 1 nT, the observed oscillations increase by 7 Hz.

A schematic diagram of an optically pumped magnetometer is shown in Figure 2.2.1.3. Light emitted from a source lamp is collimated and passed through an optical filter and a circular polarizer. The polarized light is then used to illuminate a gas cell filled with alkali metal vapors such as rubidium, cesium or helium gas. The resonance of the atom between the various energy states about an ambient magnetic field will induce absorption variation of the throughput light that is similar to the process that takes place in the resonant cavity inside a laser. A photocell detector is used to detect the phase and frequency of the exit light. The output resonance signal measured by the photodetector cell is fed back into a coil wound around the gas cell. This feedback mechanism provides fine tuning of the atomic resonance frequency of gas vapor so that it is proportional to the external magnetic field under measurement. Thus, the ambient magnetic field can be obtained by measuring the atomic resonance frequency of the gas vapor.

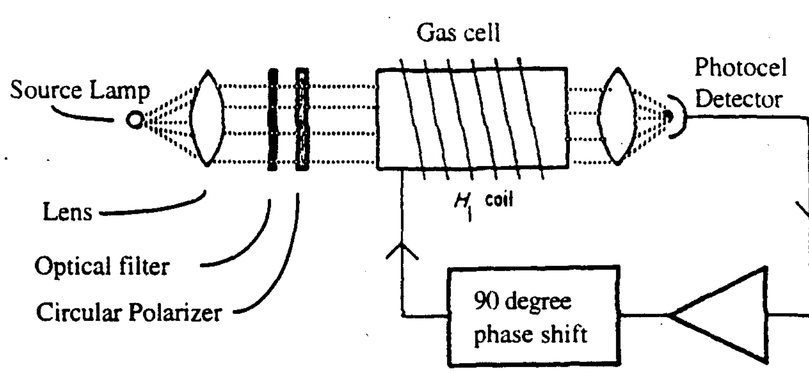

Figure 2.2.1.3 Schematic diagram of an optically pumped gas vapor magnetometer.

* This technology currently employed by the Corps of Engineers

The optically pumped magnetometer requires proper orientation in the magnetic field. The ideal angle between the sensor axis and the magnetic field is 45 or 135 degrees, plus or minus 35 degrees. Beyond those limits the Larmor signal will decrease and/or fade away.

A considerable advantage of optical pumping is that atom gyromagnetic ratios are 100 to 1000 times the proton gyromagnetic ratio, resulting in roughly ten times the sensitivity as compared to a proton precession magnetometer. Also, the pumping process is sufficiently rapid to allow continuous maintenance of the polarized condition. Both features result in higher resolution and faster sampling rates than those obtained by proton precession.

The optically pumped atomic magnetometer is also considered a "total field" sensor, due to its very dynamic ranges as well as high sensitivity. It is capable of measuring the total magnetic field intensity, which is the sum of the strong primary Earth's magnetic field (35,000 - 60,000 gammas) and the weak secondary magnetic field generated from the buried ferrous ordnance (as low as 0.001 gamma).

2.2.1.3. * Single-Axis Fluxgate Magnetometer

A fluxgate sensor is a solid-state device for measuring the magnitude and direction of the direct current (DC) or low-frequency alternating current (AC) magnetic field in the range of 0.01 to 50,000 nT (1 nT = 1 gamma). Fluxgate sensors are solid-state devices without any moving parts. They are reliable and rugged and they have low energy consumption. While the sensitivity of a fluxgate magnetometer can reach 0.01 gamma resolution and 1 gamma long range stability, 0.1 gamma resolution is standard in commercially produced devices.

The basic fluxgate sensor schematic is illustrated in Figure 2.2.1.4. In operation, the soft magnetic material of the sensor core is periodically saturated by the excitation field, which is produced by the excitation current I_{exc}. Hence the core permeability change and the DC flux caused by the external DC magnetic field B_o is modulated. A voltage V_{ind} proportional to the measured field intensity is induced in the sensing (pick-up) coil at the second and higher harmonics of the excitation frequency. An electronic tuning circuit is used to detect this frequency.

The stability of fluxgates as magnetometers depends on the magnetic and mechanical stability of the sensor itself. For example, a change in magnetization of the core can occur due to thermally produced strain and thermal dependence of the coil characteristics. (The electronic detection system is also susceptible to thermal stability problems.)

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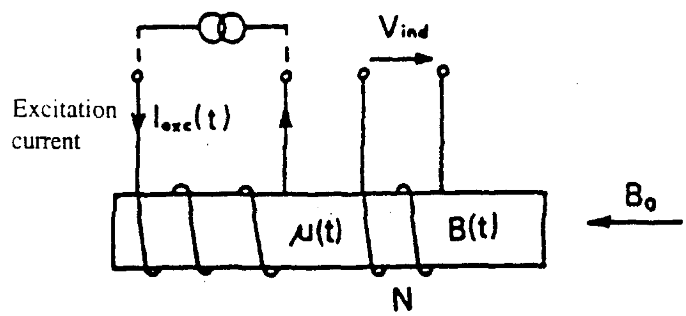

Figure 2.2.1.4 Basic fluxgate magnetometer sensor configuration

2.2.1.4. Superconducting Quantum Interference Device (SQUID) Magnetometer

Magnetometers based on SQUIDs are the most sensitive devices for measuring weak magnetic fields. Due to the use of a superconducting coil that is operated at liquid helium temperature (4.2 K), the signal-to-noise ratio is the highest among all the magnetometers existing to date. The extremely low noise level, and hence the sensitivity of a SQUID magnetometer, enables it to be used for extremely remote applications, such as underwater mine detection. It could also be a very effective tool for buried ferrous metal ordnance detection, operated from either the ground or from the air.

The direct current (DC) SQUID is the most sensitive type compared with radio frequency (RF) and microwave SQUIDs. One example of a DC SQUID's sensitivity is that it has been widely used in biomagnetism such as for brain wave measurement.

A standard DC SQUID system that operates with liquid helium is shown within the dotted line border of Figure 2.2.1.5. It consists of three components; from left to right they are: the pick-up circuit, the SQUID, and the feedback electronics. The pick-up circuit in Figure 2.2.1.5 is a wire-wound axial first-order gradiometer with a low coil acting as the field detection element and an upper coil as a reference. The pick-up coils are connected to the input coil of the DC SQUID, which consists of a superconducting loop interrupted by two resistively shunted Josephson junctions. The SQUID is operated in a flux-locked loop (FLL) in order to provide a linear relation between the magnetic flux in the pick-up coils and the output voltage of the system. An AC flux is applied to the SQUID at the bias current input in Figure 2.2.1.5, having a peak-to-peak amplitude of half of the flux quantum (flux density) and a frequency of 100 KHz. The resulting AC voltage is stepped up by a cooled impedance matching circuit, amplified further at room temperature, lock-in detected, integrated, and fed back as a current into the

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feedback coil in order to null the flux in the SQUID. Alternatively, the feedback current may be inserted into an "external" feedback coil, nullifying the current in the pick-up coils and thereby eliminating crosstalk in multichannel systems.

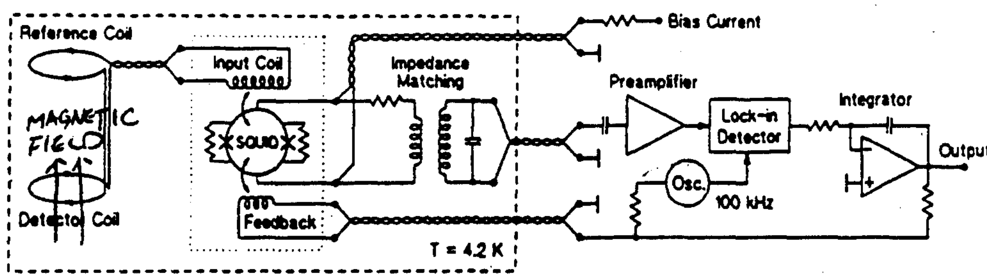

Figure 2.2.1.5 Standard DC SQUID magnetometer system with flux modulation and impedance-matching circuit

2.2.1.5 Introduction to Magnetic Field Intensity Measurements Around Buried Ferrous Metal Ordnance

The response to a buried steel object may be approximated by that from a spherical source whose mass approximates that of the buried metallic object of interest. The peak total field anomaly from this sphere in a vertical magnetic field is given by

$$T = \frac{2kFV}{r^3}$$

where
T is the peak total field anomaly measured in γ
k is the volume magnetic susceptibility of steel (a unitless characteristic)
F is the magnetic field strength, in nT
V is the volume of the sphere in cubic meters, and
r is the distance between the source and sensor in meters.

Note: 1 nT (or nanoTesla) is equivalent to 1 γ (gamma); it is the basic unit of measuring magnetic field intensity.

The gradient peak vertical magnetic field intensity ("Vertical Gradient," or "VG") is given by the first derivative of T, which is

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$$VG = \frac{6kFV}{r^4}$$

Thus, the magnetic field strength and the vertical gradient could also be computed from the known ordnance of mass m by using VG = m x D.

For example, a 10 kg steel sphere has a volume of $2x10^{-3}$ m^3, and the density of iron is 5 x 10^3 kg/m^3 'k' is given as 0.1, and the magnetic field strength is 60,000 nT. By applying the equations shown above, the total field and vertical gradient peak amplitudes with various source-sensor separations can be calculated, some examples of which appear in Table 2.2.1.5.1:

Table 2.2.1.5.1 Total Field and Vertical Gradient Peak Amplitudes for a Steel Sphere With Various Source-Sensor Separations

Measurement	Source-Sensor Separation (m)				
	1	5	10	20	40
Total Field (T, given in nT)	2400	19.2	2.4	0.30	0.038
Vertical Gradient (VG, given in nT/m)	7200	11.5	0.72	0.045	0.0028

These magnetic field intensities are proportional to the mass of the sphere and may therefore be scaled for larger or smaller objects.

Modern airborne magnetometers have a resolution of 0.001 nT but in use, noise levels are in the order of ±0.01 nT at a 0.1 second sampling rate, exceeding the sensitivity of the instrument. With noise as the limiting factor, we conclude from Table 2.2.1.5.1 that a buried 10-kg steel object may be detected with source-sensor separation of about 20 meters. If this ordnance is 5 m under the surface, it might be detected by a helicopter-borne geophysical survey, where the sensor terrain clearance is maintained at 15 m.

Total field anomalies that form a spherical source in a vertical magnetic field have a full width at half maximum amplitude which is about equal to the source-sensor separation. The overlap between successive strip samples during an airborne survey should therefore be matched to the specified terrain clearance.

2.2.2. * Electromagnetic Induction

Detectors operating on the principle of pulsed electromagnetic induction are routinely used to detect metallic objects buried near the ground surface. These sensors exploit the characteristic that when a metallic object is subjected to a pulsed magnetic field, eddy currents are induced within the object. A basic sensor consists of a pair of separated coils: one for transmission of a low-frequency electromagnetic pulse wave into the ground, and the other for reception of these eddy currents. Figure 2.2.2.1 illustrates this two-step process. Step one (the left half of Figure 2.2.2.1) involves generating a magnetic field pulse, whose duration is typically measured in milliseconds. After the pulse ends, the presence of an object can then be inferred by detecting the secondary magnetic field produced by the decaying eddy currents (right half of Figure 2.2.2.1).

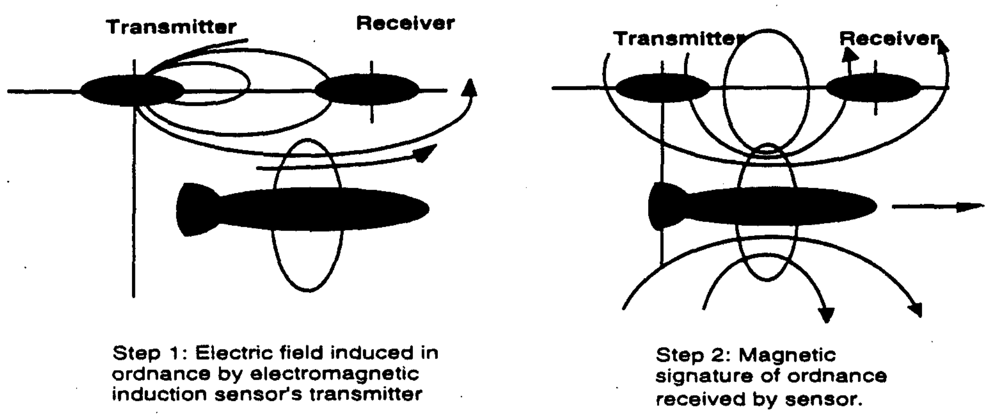

Figure 2.2.2.1 Operation of an electromagnetic induction sensor

For the detection of buried unexploded artillery shells, the capability to determine depth, size, and other parameters of the detected objects is desirable. For this application, one must be able to detect small metallic objects at shallow depths (0-2 m). ("Small metallic objects" typically have dimensions of 2-15 cm. in diameter, 5-70 cm. in length, 0.1-43 kg. in mass, metallic conductivity $\sigma = 10^7$ ohm•meter^{-1}.)

State-of-the-art electromagnetic induction sensor systems offer multiple coil configurations (with different orientations) operating at different frequencies. Simultaneous operation of these coplanar and coaxial transmit and receive coil

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pairs will produce relatively characteristic and unambiguously shaped signatures that correspond to the physical shape of the ordnance.

An example of a multifrequency, multicoil electromagnetic induction sensor is illustrated in Figure 2.2.2.2. The elongated shape within the figure represents a bird's-eye-view of a seven-meter-long sensor platform, with both horizontal and vertical transmit coils on the left side, and similarly oriented receive coils on the right.

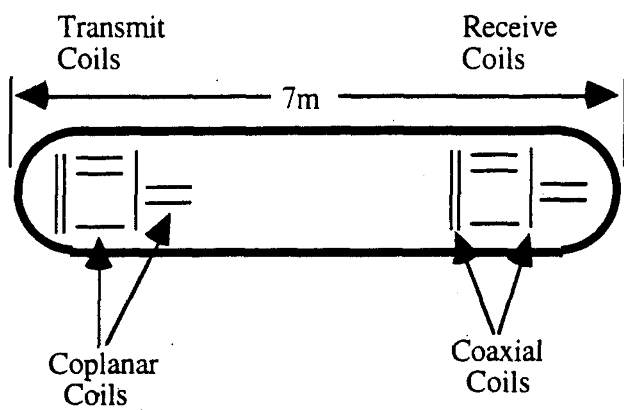

Figure 2.2.2.2 System geometry of a multicoil, multifrequency electromagnetic inductor sensor system

For any given buried metallic object, its conductivity can be inferred by measuring the phase shift between the primary and secondary fields. In most survey environments, the in-phase signal (which occurs when the transmitted and received signals are of the same amplitude without phase shift) and quadrature signals (when the transmitted and received signals have a second-order or quadratic phase shift) are positive and the phase shift is restricted to within 90 degrees. As a result, a high ratio of in-phase to quadrature response corresponds to a small phase shift and therefore a higher conductance of the buried object.

The primary advantage of electromagnetic induction sensors for buried ordnance detection is that these sensors are sensitive to all types of metals, ferrous or nonferrous (e.g., aluminum, copper, iron, steel). The electromagnetic induction sensor could also be used in conjunction with a magnetometer sensor for enhanced buried metallic ordnance detection.

An airborne electromagnetic inductor sensor system could be used to measure the conductance of the ground terrain. Although the airborne sensor's resolution would be lower than that of a ground-towed EM sensor, the airborne system would be able to quickly detect very large collections of deeply buried ordnance by noting a change of conductance in a general region. A map showing contours of equal conductance (i.e., terrain pixels having the same conductance are connected together into a contour; this map contains multiple contours of various conductance values) could be generated from such an airborne survey. Over an area where large amounts of metallic ordnance are buried underneath, the conductance will be lower than its surroundings. Thus, clusters of sites containing buried ordnance could be identified from the conductance map.

Many such airborne survey systems have been built and used for various detection applications. For example, as illustrated in Figure 2.2.2.3, an airborne electromagnetic inductor system can be used for nuclear-waste disposal-site measurement. In this figure, an electromagnetic induction sensor consisting of a coaxial coil pair emitting 935 Hz and 4600 Hz signals and a coplanar coil pair emitting 4175 Hz and 32000 Hz signals, is towed underneath a helicopter.

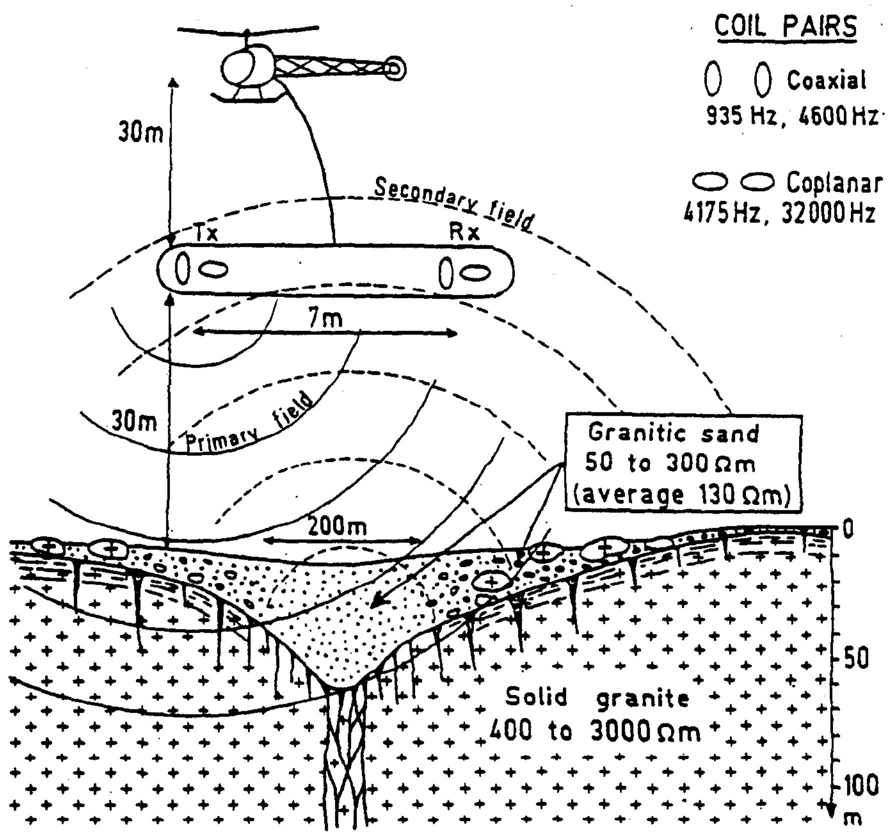

Figure 2.2.2.3 An airborne electromagnetic system for the detection of nuclear waste disposal via the measurement of granite rock conductance. (Illustration not to scale.)

In practice, the primary field is transmitted from the left set of coils into the soil, which could have a penetrating depth of up to 100 meters due to the low frequencies chosen. The ground, due to its low conductivity, emits a secondary magnetic field back into the receiving coils on the right side of the system. The received magnetic field's in-phase and quadrature components are measured. From these parameters, the conductance of the soil and rock can be inferred. Since solid granite has a higher resistance than granite sand, it is easy to distinguish between these two substances. If there are areas containing buried metallic ordnance, then these will show up as areas of lower conductance in the airborne survey.

2.2.3. * Ground-Penetrating Radar (GPR)

Ground-penetrating radar has been widely perceived as one of the most powerful remote sensing instruments capable of locating buried objects beneath the ground. Typically, GPR is the only instrument that is able to collect images of buried objects, as compared to magnetometers and electromagnetic induction sensors, which usually only detect the presence of objects. Moreover, due to its unique capability of detecting both metallic and nonmetallic sub-surface and buried objects, it could be used to detect buried ordnance possessing either a metallic or plastic shell; it could also be used to detect buried toxic chemical waste stored in glass containers.

There are, in general, two broad categories of ground-penetrating radar (GPR): ground-based and airborne. The term 'ground-based' refers to sensor systems that are operated at a distance within a tenth of a wavelength of the ground in order to minimize surface reflections and to maximize the transfer of energy into the ground. In the past, GPRs have been so large and bulky that ground-based systems almost exclusively had to be ground-towed, as handheld implementations were difficult to achieve. (Although today, man-portable units are becoming available.) Airborne sensors are defined as anything that operates above this threshold, including helicopters, airplanes, and satellites. With airborne GPR the transmission through the air-ground boundary has to be addressed, hence the need for the distinction.

There are also two major categories of radar signal processing: time-domain and frequency- domain. Time-domain radars use short impulses of energy to actively illuminate the are being surveyed; frequency domain radars use a continuous transmission where the frequency of the signal is varied either stepwise or continuously over a range of spectral content. Signal processing then processes and converts this data back to a time-domain format. Finally, time-domain GPRs can be broken down into narrow-band and ultra-wideband, as discussed in the

* This technology currently employed by the Corps of Engineers

next two sections. None of the above-mentioned categories are necessarily mutually exclusive; for example it is possible to have an airborne ultra wide band synthetic-aperture radar which employs impulses.

The rest of Section 2.3 discusses technical issues relating to the principle of radar imaging, resolution (range and azimuth), factors affecting the ground-penetrating depth and resolution, and image-forming post-processing algorithms as they apply to both ground-based and airborne GPR.

2.2.3.1. * Narrow-Band Radar

Figure 2.2.3.1.1 is a diagram of the components of a typical single-antenna radar system. The pulse-generating device in the upper-left-hand corner produces pulses of electromagnetic energy that serve two purposes: (1) they control the bursts of energy from the transmitter, and (2) they trigger the sweep of the CRT (cathode-ray tube) and/or film-recording device. (Modern systems display and record the information digitally, but the principles remain the same.) The bursts of electromagnetic energy from the transmitter are of a specific wavelength and duration, or pulse length. The same antenna transmits the radar pulse and receives the return from the terrain. An electronic switch or duplexer prevents interference between transmitted and received pulses by blocking the receiver circuit during transmission and the transmitter circuit during reception. The antenna is a reflector that focuses the pulse of energy into the desired form for transmission and also collects the energy returning from the terrain. A receiver amplifies the weak energy waves collected by the antenna. At the same time it preserves the variations in intensity of the returning pulse. The receiver also records the timing of the return pulse, which determines the position of the terrain features on the image. The return pulse may be displayed as a line sweep on a CRT and/or simultaneously recorded on a digital recorder for later computer processing.

Figure 2.2.3.1.2 shows an example of a GPR's output. This example is a scan of Sutherland Pond near Cornwall, New York. The data were taken as the radar was floated over a 20 meter length of the pond's surface. Several features are easily recognizable, e.g., the surface of the water and the bottom of the pond. Other targets appear as hyperbolas in the radar scan. These arcs represent an object; the curvature is caused by the change in distance of the objects as the GPR passes over them. The two prominent arcs appearing in the right half of the illustration are caused by tree trunks beneath the pond's bottom. Multiple hyperbolas appear due to the multiple bounces or ringing between the mud surface and the tree trunk.

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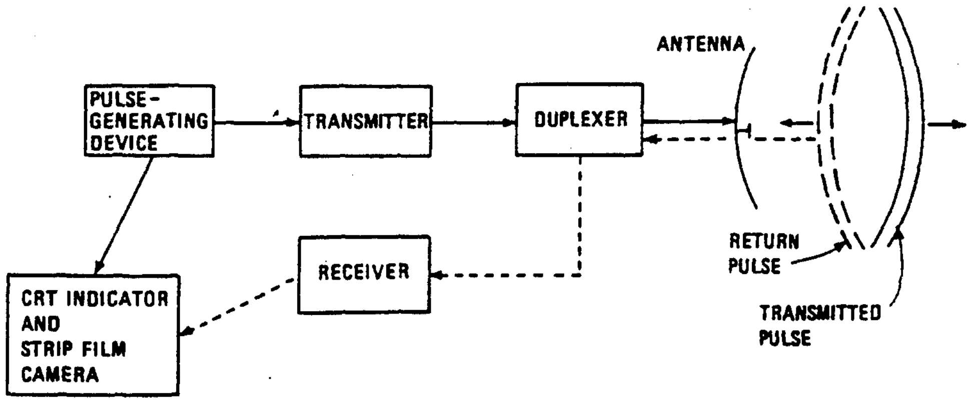

Figure 2.2.3.1.1. Block diagram of a radar imaging system

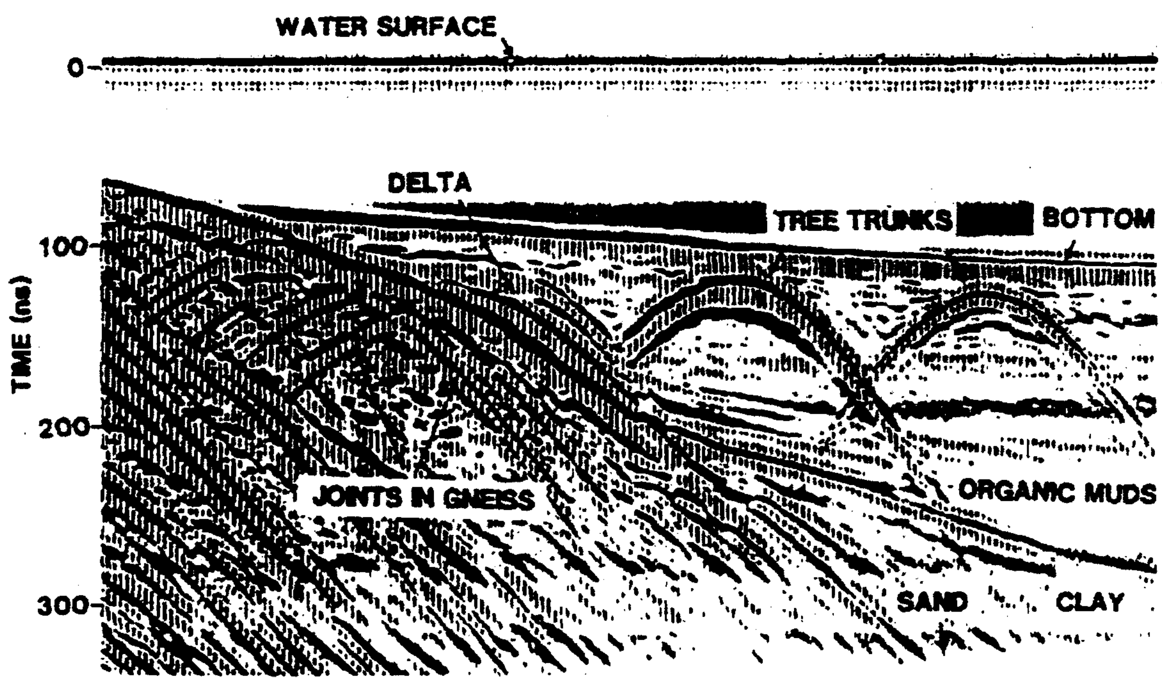

Figure 2.2.3.1.2. An example of GPR output of Sutherland Pond*

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* Source: J. S. Mallett, "Bathymetric Studies of Ponds and Lakes Using Ground-Penetrating Radar,", *Proceedings of the Second Government Workshop on GPR*, ed. U.S. Environmental Protection Agency, Region V, and the Ohio State University, (1993) pp. 257-266.

The performance of a ground-penetrating radar in terms of resolution and ground penetration depth is the result of trade-offs between the frequency, type of radar mode (ground profiler or SAR; see Section 2.2.3.3 for explanations), and polarizations. For example, as the radar frequency is reduced, the depth of penetration increases and the resolution decreases. In the case of vertical profiles, both the vertical and horizontal resolutions are improved by the fact that the wavelength in soil is much shorter than in the air. Higher resolutions are possible by increasing the radar bandwidth, a solution involving a higher price and increased complexity.

The ground penetration depth achievable by using the ground penetrating radar is also highly dependent upon the underground material, the vegetation contained within it, and its permittivity, ε. Vegetation can both attenuate the return signal and provide physical obstacles to the ground-towed sensor.

The permittivity, ε, is a complex number which measures how much a material or substance slows down and attenuates an electromagnetic wave. It is defined as:

$$\varepsilon = \varepsilon_r + \frac{\sigma}{\omega} i$$

where:
ε = complex dielectric permittivity
ε_r = dielectric permittivity (real component)
σ = conductivity (Siemens/meter)
ω = radian probing frequency ($=2\pi f$)

The conductivity, σ, is the physical property which defines how well a material conducts electric current.

Generally, GPR is most effective when the quotient (σ/ω) is less than ε_r. When this material condition is encountered, changes in ε_r primarily change the radar wave velocity, while changes in σ primarily affect the absorption of the radar signal by the medium. The larger ε_r, the slower waves travel; the larger σ, the greater the signal attenuation.

To provide more insight into the material-dependent ground-penetrating depth, approximate penetration depths of various materials are listed in Table 2.2.3.1. From this table, it can be seen that ice has the maximum penetration depth, whereas clay soil and anything with a salt content (saline) has the minimum penetration depth.

It is very interesting to note that ice (as well as other purely frozen soils) has a greater penetration depth. This would suggest that GPR site surveys should be conducted during winter when the soil is frozen, allowing greater ground penetration. However, field experiences show that there is not much difference between frozen and unfrozen soils in terms of depth of exploration with GPR.

Generally, in fine-grain soils water in the pore space does not freeze totally and the residual water content leads to a lower conductivity and therefore lower penetration depth than would be expected.

In general, the benefits of frozen soil are probably greater for airborne radars than they are for ground-based radars. With airborne radars the reflectivity of the air-ground interface is reduced because the dielectric constant is reduced even if only part of the water in the pore space freezes. In contrast, on the ground the surface reflection is not the issue but rather the attenuation in the material. If the attenuation is high when the material is unfrozen, it is unlikely to drop significantly even when the material is frozen unless the soil temperature can be reduced to -50 or -60 °C.

Table 2.2.3.1 Typical GPR Properties of Various Geologic Materials

Material	Typical Penetration Depth, m	Maximum Probing Frequency, MHz
Cold pure freshwater ice	10,000	10
Temperate pure ice	1,000	2
Saline ice	10	50
Fresh water	100	100
Sand (desert)	5	1,000
Sandy soil	3	1,000
Loam soil	3	500
Clay soil	2	100
Salt flats (dry)	1	250
Coal	20	500
Rocks	20	50
Walls	0.3	10,000

Notice that, in Table 2.2.3.1, saline ice impedes GPR penetration at low frequencies more than pure freshwater ice by a factor of 1,000. Similarly, saline water impedes GPR more than does fresh water. Soil containing a high groundwater and high levels of saline, therefore, would not be ideal for GPR. At frequencies of 500 MHz and above, one starts to approach the absorption associated with the natural relaxation of the water molecule, and as a result attenuation in fresh water tends to increase. Normally, GPRs operate at lower frequencies and therefore this effect does not dominate.

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Figure 2.2.3.1.3 is another illustration of soil attenuation properties. This graph shows the one-way attenuation of various soil types as a function of their conductivity, taken at several probing frequencies.

Figure 2.2.3.1.4 contains a map showing the estimated ground conductivity in the United States, measured in conductance. This map is derived from data collected in the 1950s, and shows only general averages. Actual soil conductivity will vary every few feet, and is sensitive to seasonal changes. But it gives enough information to generally determine which sensor technologies would be most favorable for a given region. This chart is for information only; individual sites should be fully characterized before selecting sensor types.

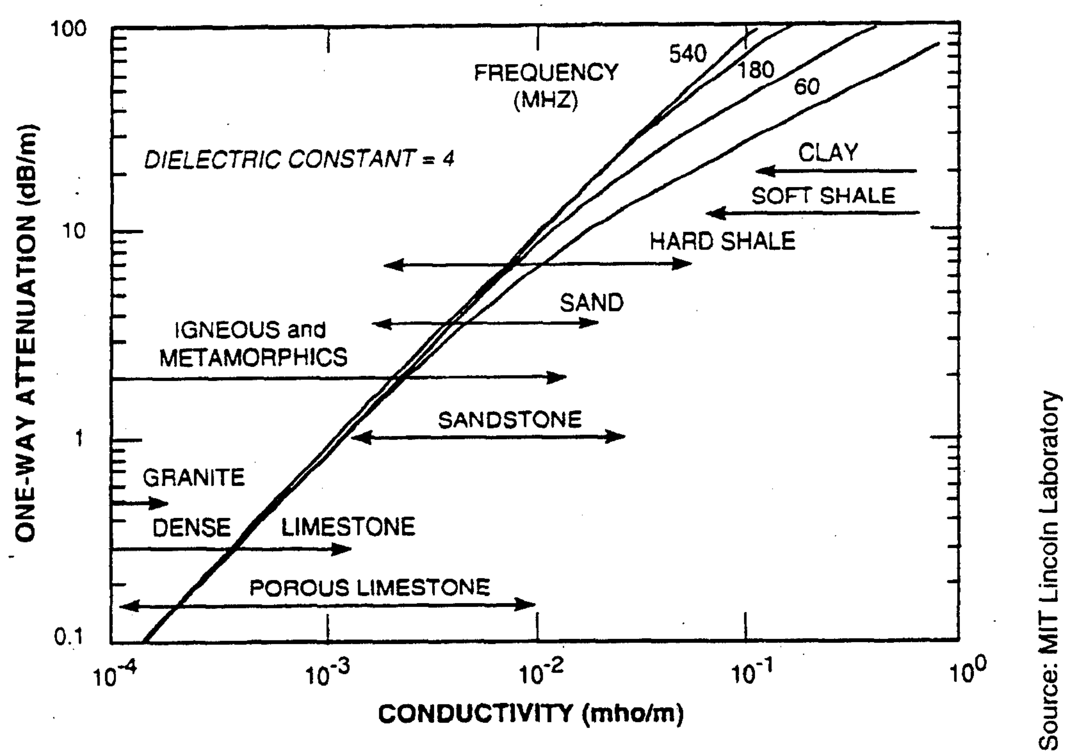

Figure 2.2.3.1.3. Conductivity vs. One-Way Attenuation Graph of Various Soils. Horizontal lines show the range of conductivity of different materials.

The polarization of radar waves also affects the performance of airborne GPR target detection. Vertical polarization (VV) will give much brighter returns from buried targets than horizontal polarization (HH), provided that the incident angle is sufficiently close to the Brewster angle. Therefore, a GPR equipped with a VV polarization would have much stronger return and better detection capabilities. Horizontal polarization (HH) is often employed when only the surface of the ground needs to be examined.

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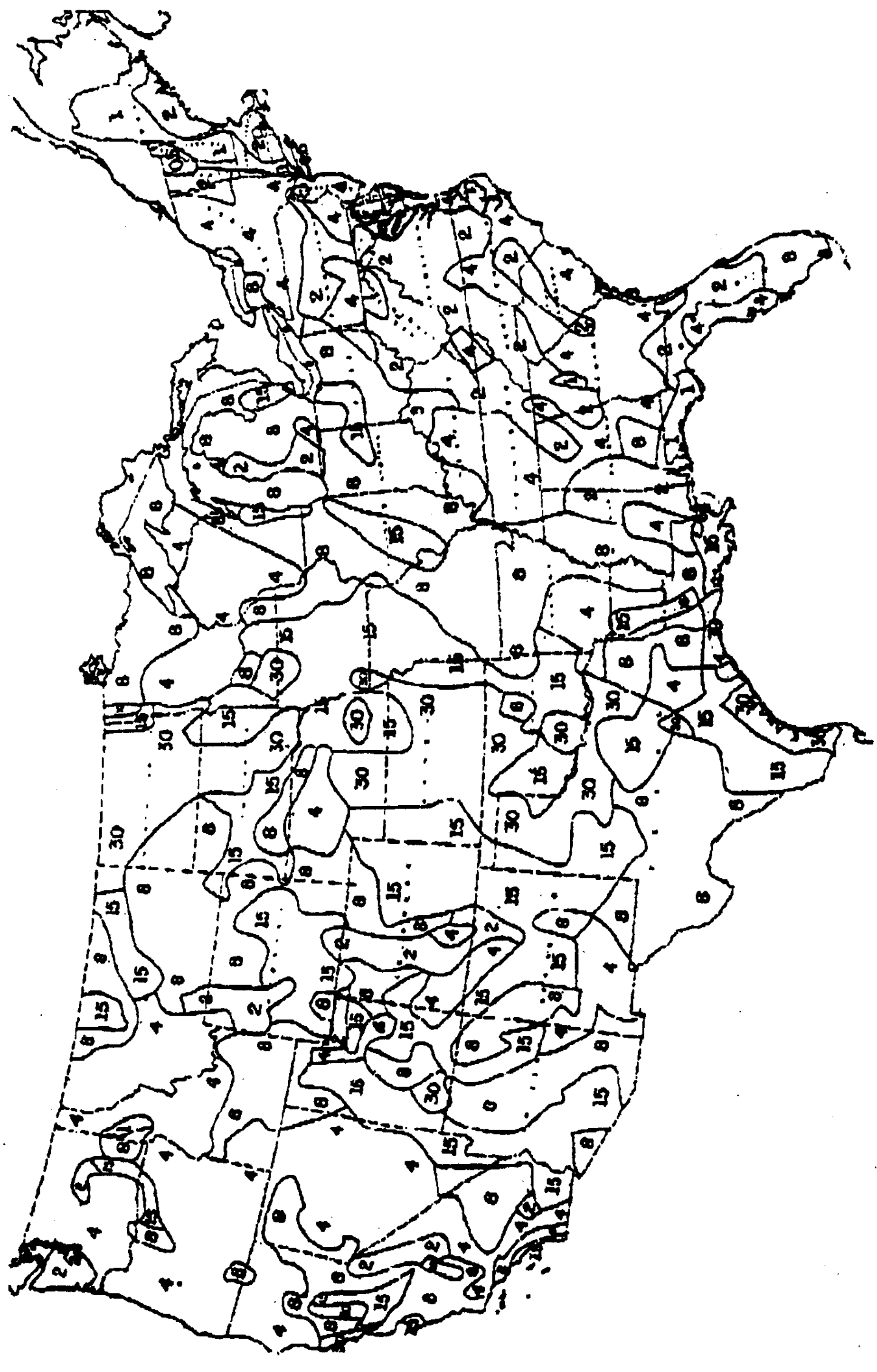


Figure 2.2.3.1.4. Estimated ground conductivity in the United States. The variations reflect varying soil composition. (Source: USGS Conductivity Map.)

2.2.3.2. Ultra-Wide-Band (UWB) Radar

As stated in the previous section (Narrow-Band Radar, Section 2.2.3.1), the range resolution of a radar system is determined by its radar transmitter pulse width; the shorter the pulse width ,the higher the range resolution and the wider the bandwidth. The relationship between a radar pulse and the system bandwidth requirement is illustrated in Figure 2.2.3.2. Assuming the transmitted pulse width of a radar signal is Δt, the corresponding frequency bandwidth Δf, as observed in the Fourier transform domain, is the half-width of the main lobe as shown in this figure. The mathematical relationship of the time-domain pulse width Δt and the frequency-domain bandwidth Δf is $\Delta f = 1 / \Delta t$.

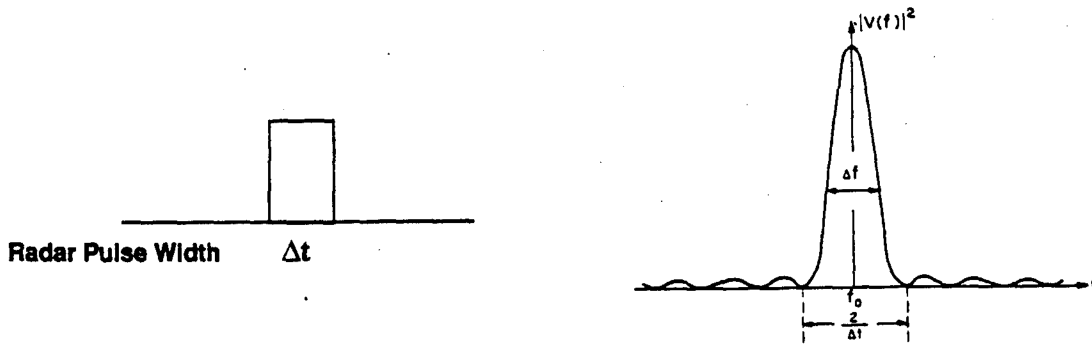


Figure 2.2.3.2. Transmitted radar pulse width and system bandwidth.

For example, a radar emitting a pulse of 10 ns duration would require a bandwidth of 100 MHz. Accordingly, a bandwidth of 200 MHz is required to achieve a 5 ns pulse width.

Thus, to acquire high range resolution (ground penetration depth resolution in the case of vertical profiler GPR), a very short radar pulse width is required (this often is called an "impulse"). To achieve optimum performance, a large bandwidth radar system has to be developed. A radar system using an impulse radar source and possessing a matching wide bandwidth receiver is sometimes called ultrawide band radar (UWB).

2.2.3.3. * Synthetic-Aperture Radar (SAR)

Radar systems generally provide a degree of resolution (detail) in an image relative to the antenna's width. The greater the antenna size (aperture), the more detail may be discerned from the obtained image. "Real" aperture radar refers to a stationary antenna with a fixed width. "Synthetic" aperture radar physically

* This technology currently employed by the Corps of Engineers

moves the antenna in straight lines over the terrain. This image has the same resolution as would a much larger antenna possessing the width of the distance traveled. Each of the reflected signals is stored onboard the aircraft or ground vehicle. If desired, the information may be further processed, displayed, printed or digitized for storage and later playback.

When the radiated signal encounters contrasts in the subsurface features, part of the signal is reflected back up to the receiving antenna, while the remaining signal continues downward to deeper material. Specifically, a portion of the signal is reflected at each change in permittivity of the subsurface terrain. It is these changes in dielectric properties which are being detected. Each reflected signal is stored. To obtain a final image, extensive processing is performed, either within the system itself or held for later processing. Post-processing reveals the locations of buried objects, be they metallic or nonmetallic, as items are identified by shape, not by presence alone.

As the distance traveled corresponds to the effective size of the antenna, aerial SARs are used for their ability to obtain quick, detailed surveys of a large area. Sizes and shapes of subsurface objects are enhanced by obtaining views of the object from parallel and/or perpendicular perspectives.

Figure 2.2.3.3.1 illustrates how the SAR works. It employs a small antenna that transmits a relatively broad beam. The extensive post-processing, however, can produce the effect of a large antenna with a very narrow, collimated beam in the azimuth direction (shown by the shaded area). For both real-aperture and synthetic-aperture systems, resolution in the range direction is determined by pulse length and depression angle.

While a GPR has reasonable range resolution, its azimuth resolution is rather limited due to the small physical aperture size that could be carried by either an aircraft or a ground-towed vehicle. Thus the azimuth resolution of a real-aperture system will be limited by its aperture size.

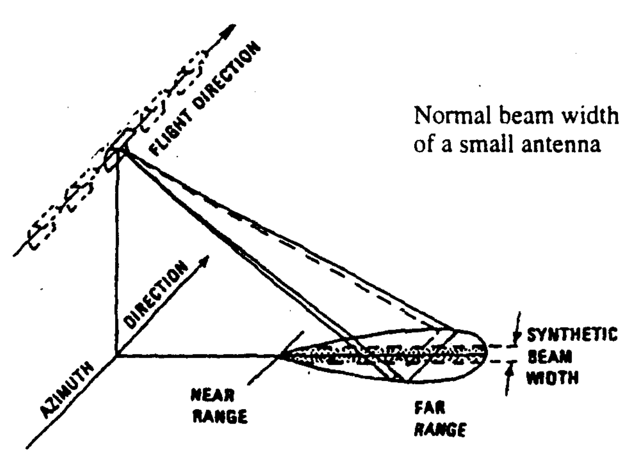


Figure 2.2.3.3.1. Synthetic-aperture radar system

Graphic descriptions of the 3-D resolution cells of both a normal vertical profiler and SAR GPR are shown in Figures 2.2.3.3.2 and 2.2.3.3.3, respectively.

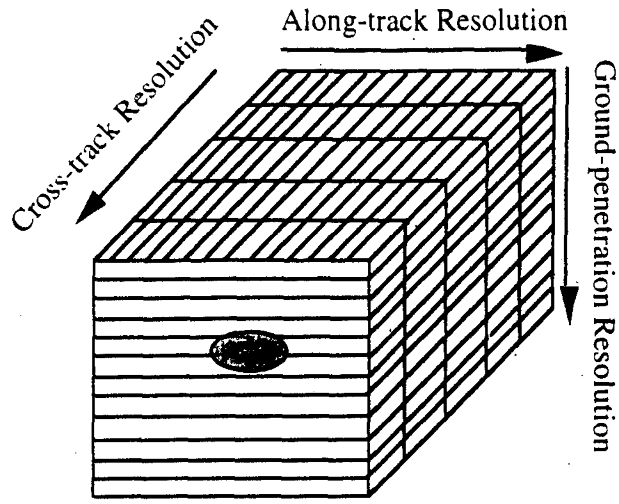


Figure 2.2.3.3.2. 3-D resolution cells of a vertical profiler ground-penetrating radar. The resolutions are 1m in the along-track direction, >30m in the cross-track direction, and 1m in the ground penetration direction

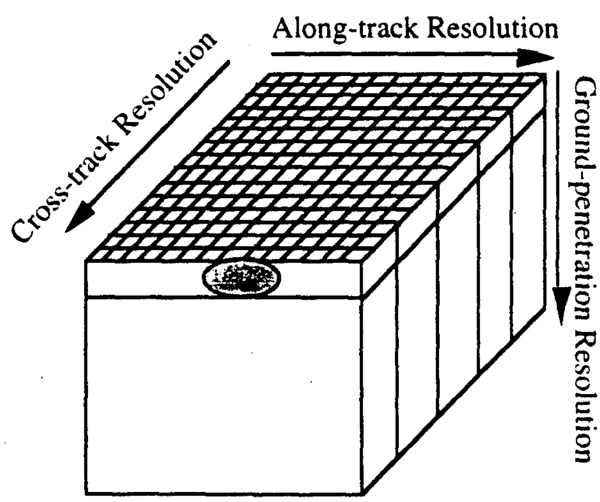


Figure 2.2.3.3.3. 3-D resolution cells of a SAR ground-penetrating radar. The resolutions are 1m in the along-track direction, 1m in the cross-track direction, and 1m in the ground penetration direction

The primary difference between the 3-D resolution charts between a vertical profiler and a SAR GPR, shown in Figures 2.2.3.3.2 and 2.2.3.3.3 respectively, is as follows:

- The vertical profiler GPR has good along-track resolution, but the cross-track resolution is much poorer, resulting in a 1-D scan of the depth information of underground terrain.

- The SAR GPR has good along-track as well as cross-track resolution. However, it lacks good resolution along the ground-penetration direction. Thus, a SAR could be used for high-resolution large-area subsurface surveillance to identify possible OEW burial sites.

2.2.3.4. Frequency Modulated Continuous Wave (FM-CW) Radar)

FM-CW radars have been used for ground penetration to holographically image subsurface targets. These transceivers record the phase difference between the transmit and receive signals across an aperture. The data are processed to produce a vertical profile or horizontal image. FM-CW is used for radar applications where the targets of interest are buried near the surface (less than 2m) and a wide transmitted bandwidth is required. There are typically two types: 1) stepped frequency (where impulses of fixed, ascending and descending frequencies are sequentially stepped through) and 2) continuous frequency, where the frequency sweeps occur while radar return is being read. Both types penetrate the ground at frequencies throughout the full sweep band, allowing it to adapt to a wide variety of soil types and locate different sized ordnance buried at varying depths.

The transmitted signal of a FM-CW radar is continuously swept in frequency (full-band) back and forth about a center frequency. The currently transmitted frequency is also sampled and fed into the radar receiver. This sample frequency is then compared with the returned radar signal in a radar mixer to provided the time delay, and hence range, of the buried objects.

Although the time-domain waveform of an FM-CW radar signal is different from that generated by an impulse radar, the Fourier transforms of both the FM-CW and the impulse radar source are very similar. Therefore, the performance of a FM-CW radar could be similar to that of an impulse radar. By using a large frequency bandwidth, an FM-CW radar could also be made into an ultra-wide-band (UWB) radar system. The main advantages of the FM-CW radar are simplified control of transmitted spectral shape, and a higher signal-to-noise ratio in the processed radar image.

Implementation of FM-CW systems requires careful control of the frequency sweep and of the mixing process. These control steps include:

a) linearity of frequency sweep with time to minimize degradation of resolution due to spectral broadening;

b) purity of spectral output to avoid the generation of in-band intermodulation products in the output of the mixer which will degrade the clutter performance of the radar; and

c) stability of the frequency output.

The theoretical shortcoming of an FM-CW system is its inherent need for sophisticated signal processing to recover the time waveform required for interpretation and display of the results. There is also a potentially greater risk of producing electromagnetic interference unless a very large number of frequencies, each at a very low power level, is used.

2.2.3.5. Airborne GPR

There are several drawbacks that limit the applicability of the land-based ground-penetrating radar: 1) it is restricted to use in areas without thick vegetation which would impede the ground-towed platform's path, 2) it is operated at low-speed which extends site survey times, and 3) it is basically restricted to the vertical profiling mode, which means no surface imaging can be performed.

Airborne GPR can alleviate these drawbacks. Moreover, the side-looking synthetic-aperture radar (SAR) GPR enables fine resolution in both the along-track (azimuthal) resolution and the cross-track (range) resolution (defined below).

Airborne GPR is defined as those radars whose antennas are more than one tenth of a wavelength above the ground, where transmission through the air-ground boundary has to be addressed. Airborne GPRs also require much higher transmitter power and receiver sensitivity. The high-moving speed of the aircraft (fixed-wing or helicopter) also results in a higher data rate. Complex on-board processing hardware is therefore required to enable the real-time processing capability for in-flight image display. All of these special characteristics warrant this section on the special problems of airborne GPR.

The two important criteria for measuring performance of airborne-GPR are azimuth resolution and range resolution. Azimuth resolution, R_a, is determined by the width of the terrain strip illuminated by the radar beam. To be resolved, targets must be separated in the azimuth direction by a distance greater than the beam width as measured on the ground. As shown in Figure 2.2.3.5.1, the fanshaped beam is narrower in the near range than in the far range, meaning higher resolution measurements are possible in the near-range portion of the image. The width of the beam is directly proportional to the wavelength of the transmitted energy; therefore azimuth resolution is higher for shorter wavelengths, but the short wavelengths lack the desirable ground penetration capability. Angular beam width is also inversely proportional to antenna diameter; therefore, resolution improves with longer antennas, but there are practical limitations to the maximum antenna length.

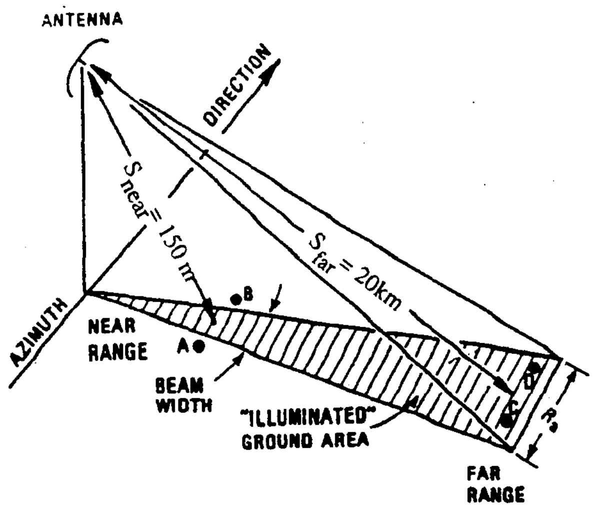


Figure 2.2.3.5.1 Radar beam width and resolution in the azimuth (forward flight) direction

The equation for azimuth resolution (R_a) is

$$R_a = \frac{0.7\lambda S}{D}$$

where

S is the slant-range distance,
D is the antenna length, and
λ is the wavelength,

all the above units being in meters. For a typical GPR:

frequency f = 250 MHz

$$\text{wavelength } \lambda = \frac{c}{f} = \frac{3\text{x}10^8 \text{ m/s}}{250 \text{ Mhz}} = 1.2 \text{ m.}$$

For D = 1 meter at the near-range position, and for a slant range of 150 m,

$$\text{then } R_a = \frac{(0.7\,\lambda S)}{D} = \frac{(0.7)(1.2\text{ m})(150\text{ m})}{1\text{ m}} = 126 \text{ meters.}$$

Resolution in the range direction (the direction in which the antenna is pointing) and azimuth (flight) direction is determined by the engineering characteristics of the radar system. Range resolution R_r, is theoretically equal to one-half the pulse length, τ. It is converted from time into distance by multiplying by the speed of electromagnetic radiation (the speed of light, "c", or 3 x 10^8 m/sec). It is then divided by $2\sin(\gamma)$ to compensate for return path and probing angle.

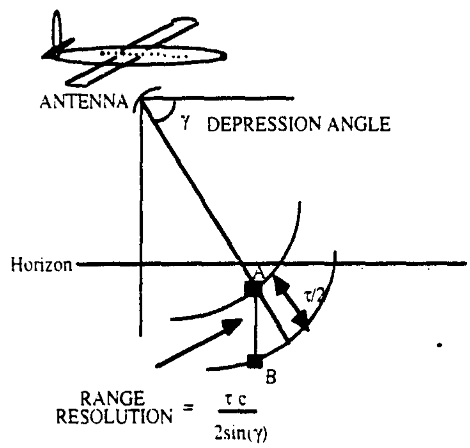


Figure 2.2.3.5.2 Radar resolution in the range direction (the direction in which the antenna is pointing)

Figure 2.2.3.5.2 shows the vertical range resolution between two buried underground points, A and B. For example, if the depression angle is 45 degrees and the pulse length is 10 ns, the range resolution is

$$R_r = \frac{\tau c}{2\sin(\gamma)} = \frac{(10 \times 10^{-9})(3 \times 10^{8})}{2\sin(45)} = 2.12 \text{ meters}$$

For a vertically down-looking GPR (also called a vertical profiler GPR), the depression angle is 90 degrees and the range resolution, R_r, would be 1.5 meters.

2.2.3.6 Polarized Radar Waves

The principle of operations for HH and VV modes are illustrated in this section. By appropriately configuring the transmission and receiving antennas of an imaging radar (real-aperture or SAR), the radar can be tuned to four possible polarization modes: HH (horizontal transmission, horizontal reception), HV, VH, and VV (vertical transmission, vertical reception).

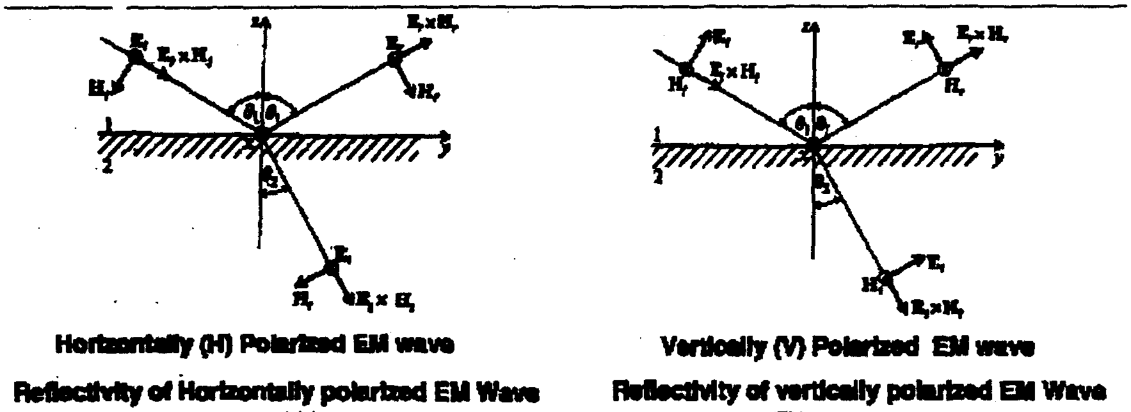
For conventional surface imaging, HH polarization mode is most frequently utilized due to its optimum surface reflection. For ground-penetration applications, the VV polarization mode is preferred for its optimum ground penetration.

The definition of horizontal and vertical polarization of an EM wave is shown in Figure 2.3.3.6 (a) and (b), respectively. In Figure 2.3.3.6 (a), the incident electromagnetic wave whose electrical field is parallel to the plane of interface between the two dielectric materials (in this case, air and ground), is defined as a horizontally-polarized beam. Upon hitting the ground, part of the beam is reflected back into the air, and part penetrates into the ground soil. According to Snell's Law, the reflectivity is defined as:

$$R_h = \frac{\cos\theta_1 - n_{12}\cos\theta_2}{\cos\theta_1 + n_{12}\cos\theta_2}$$

where θ_1 and θ_2 are the incidence and reflection angles respectively, and n_{12} is the relative refraction index between the air and the ground soil..

The reflectivity, R_h, of this horizontally polarized wave is greater than zero at any incident angle, thus it is highly desirable to use an HH-polarized beam for surface imaging in which maximum surface return is desired.



(A) (B)

Figure 2.2.3.6. VV Polarized Radar Wave for Better Ground Penetration.

As shown in Figure 2.2.3.6 (b), the incident EM wave whose magnetic field is parallel to the plane of interface between the two dielectric materials (in this case, the air and ground), is defined as a vertically-polarized beam. Reflectivity of a vertically-polarized incident beam is defined as:

$$R_p = \frac{n_{12}\cos\theta_1 - \cos\theta_2}{n_{12}\cos\theta_1 + \cos\theta_2}$$

It is interesting to note that when the incident angle reaches the Brewster angle, i.e. tan $\theta = n_{12}$, the surface reflectivity R_p is equal to zero. Thus, by appropriately tuning the radar depression angle, most of the radar wave could be transmitted into the ground, resulting in a maximum penetration depth. Therefore, a VV mode radar wave is required for use in ground-penetration applications.

2.2.4. * Visible Imaging

Imaging can be defined as the reproduction of an object produced by electromagnetic rays. Visual imaging is that reproduction formed by light rays falling within the wavelength range of 380 to 760 nm, as illustrated in Figure 2.2.4.1.

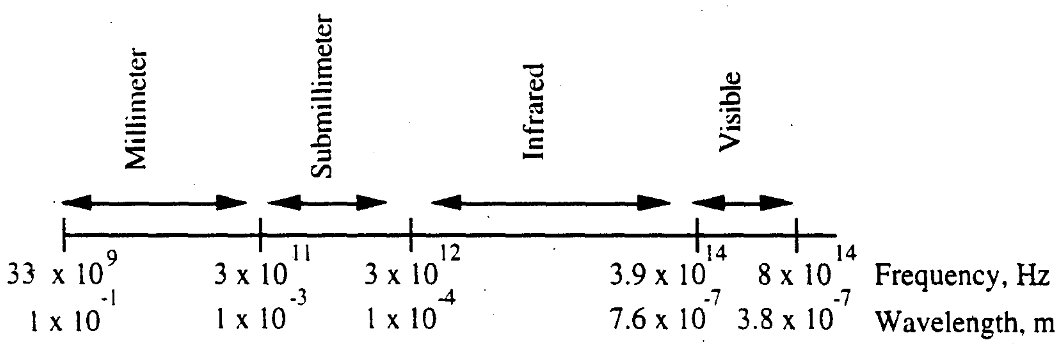


Figure 2.2.4.1 Electromagnetic Spectrum

An imager (e.g., a camera) is an image-forming optical system that gathers a beam of light from an object point and transforms it into a beam that converges toward or diverges from another point, thus producing an image. A visual imager is the obvious first choice for conducting surface scanning or area mapping of an OEW site. As an example, the application of a film-loaded camera for aerial reconnaissance is as old as the airplane itself. Newer, state-of-the-art imagers capable of resolution to a few centimeters are readily available and universally applied. For these electronic imagers, the image is captured by a detector which sits on the focal plane where the film is normally located in a conventional camera. These detectors are transducers that convert the photon energy received

* This technology currently employed by the Corps of Engineers

into an electrical output where the signal is electronically processed and displayed.

One of the most dramatic detector innovations in recent years has been the introduction of the charge-coupled device (CCD). The CCD is simply a means of controlling the movement of signal electrons by the application of electric fields. It shifts a group of signal electrons from input to output without distorting the signal itself.

Present silicon CCDs have a bandwidth covering 0.4 to 1.1 micrometers. The limits have been extended to below 0.2 micrometers for specially coated silicon devices. A CCD detector with a depiction of its principle of operation is presented as Figure 2.2.4.2.

PRINCIPLES OF OPERATION

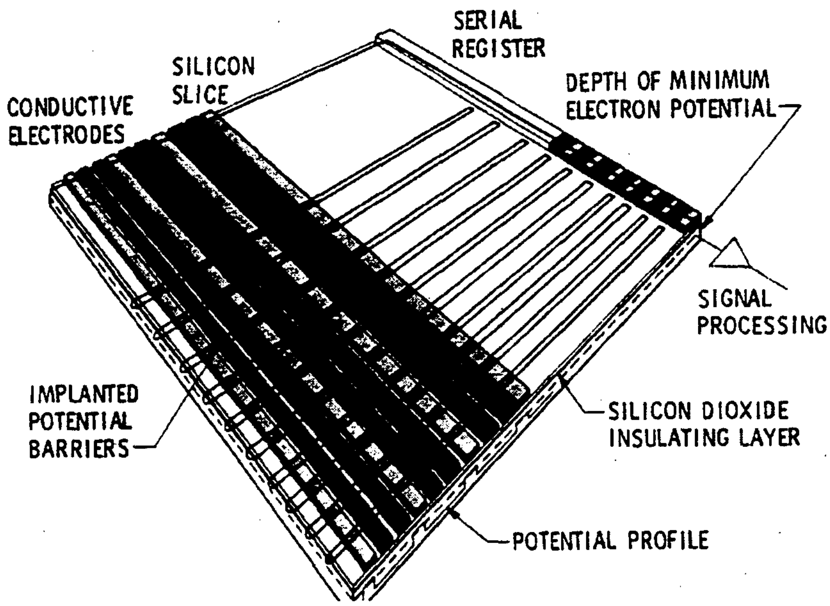


Figure 2.2.4.2 CCD Principles of Operation

2.2.5. * Infrared (IR) Radiometry

Infrared (IR) radiometry applies to the wavelengths between 0.76 μm (7.6×10^{-7} m) and 100 μm (1×10^{-4} m), as illustrated in Figure 2.2.4.1. Radiometry is the measurement of energy (emitted or reflected) from an object or a surface in a quantitative manner.

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* This technology currently employed by the Corps of Engineers

It is important to recognize the differences between reflected and radiated energy, particularly in the infrared region. When viewing an object such as the Earth during daytime, reflected solar energy (approximately 6000 K) predominates through the near, short wave, and mid-wave IR bands. The subdivisions of the infrared range are shown in Table 2.2.5.1. The emission of the Earth (approximately 300 K) becomes stronger in the mid-wave band and exceeds the reflected fraction at about 7 µm. At night, nearly all the radiation appears in the thermal infrared bands, comprised of re-radiation of absorbed solar energy shifted down in frequency, and internal heat from the Earth's center.

Table 2.2.5.1 Subdivisions of the Infrared Range

Designation	Abbreviation	Wavelength Range in Microns (µm)
Near IR	NIR	0.76 to 1
Short-Wave IR	SWIR	1 to 3
Mid-Wave IR	MWIR	3 to 7
Thermal IR	TIR	7 to 15
Far IR	FIR	15 to 100

Due to atmospheric absorption effects, IR imaging systems for terrestrial applications are confined to the range of mid-wave-infrared (MWIR) and thermal-infrared (TIR) bands where the earth's atmosphere is relatively transparent. In the far-infrared range, the atmosphere is essentially opaque for paths more than a few meters long.

There are two basic types of infrared radiometer systems available for terrestrial applications:

1. Single-wavelength thermal system (MWIR or TIR)
2. Double-wavelength thermal system (MWIR and TIR)

* 2.2.5.1. Single-Wavelength Thermal Systems

Selection of an infrared system for the OEW task depends on particular site circumstances: is there predominantly emitted or reflected radiance; what is the target temperature and what is its contrast with the background; what is the typical signal-to-noise ratio; how will the system be deployed, and what financial constraints exist? Hotter objects radiate more energy and are thus more easily detected by their emitted signal (see Figure 2.2.5.1). TIR detectors are the most

* This technology currently employed by the Corps of Engineers

sensitive to this radiation, but MWIR systems have been used successfully as well.

Signal-to-noise ratio (Figure 2.2.5.2) is a function of contrast ratio (Figure 2.2.5.3) for objects at differing temperatures as a function of wavelength. The decision to choose between MWIR and TIR sensors (or both) should be based on the sensors' optimizing signal, SNR and contrast for the specific application.

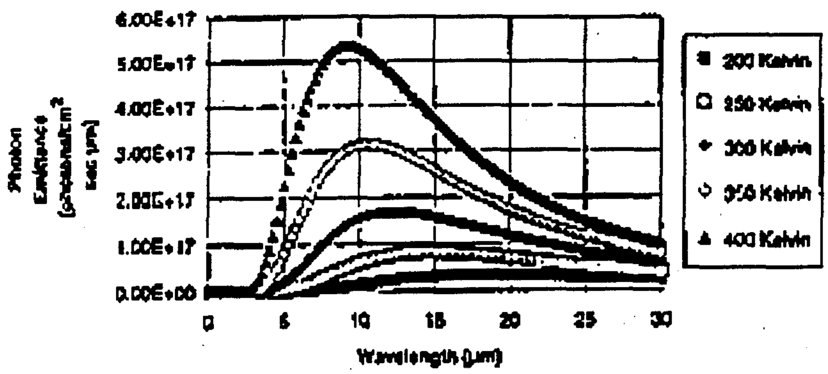


Figure 2.2.5.1. Radiant Emittance vs. Wavelength for Selected Temperatures

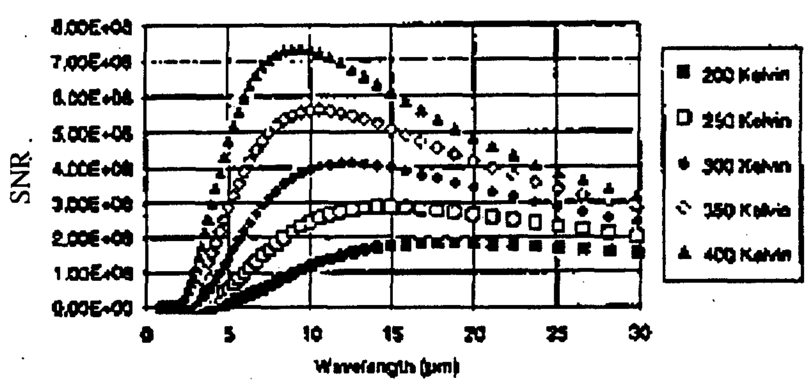


Figure 2.2.5.2. SNR vs. Wavelength for Selected Temperatures

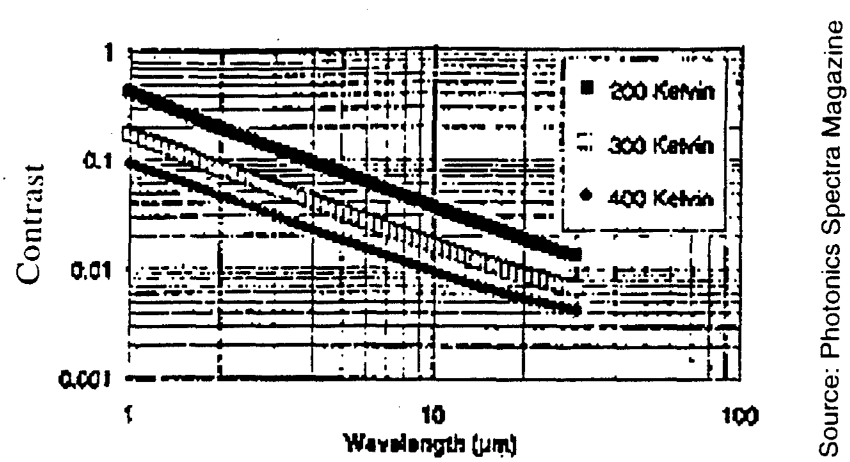


Figure 2.2.5.3. Contrast vs. Wavelength for Selected Temperatures

There are many potential uses of IR instrumentation for OEW remediation. Explosive casings, ferrous or otherwise, usually have much higher thermal conductivity than their dirt surroundings. When illuminated by sunlight, they reach a much higher equilibrium temperature and stand out from the thermal background if not deeply buried or otherwise obscured. Likewise, since these items lose heat only by conduction to the atmosphere and the ground, they will remain as hot spots in the late afternoon or evening after the surrounding surface has cooled.

Buried munitions have, by the process of becoming buried, disturbed the ground locally, resulting in local variations in the thermal signature. These characteristics remain even after the surface indications of the impact have been removed by weathering.

A more powerful approach examines the resulting variation in thermal lapse rate during evening cooling. This can be discerned by viewing the same area at two sequential times with a calibrated thermal imager and noting the difference in rate of change of temperature. Similarly, the textural changes caused by impacting ordnance are readily seen in comparison with undisturbed surroundings by near infrared (NIR) and single-wavelength infrared (SWIR) imagers, particularly those having the additional capability to determine the degree of polarization of the reflected radiation compared with undisturbed terrain.

The capability to detect buried ordnance using IR technology has been demonstrated on many occasions in the past. The Army has used the technique successfully to detect minefields from airborne platforms in a single pass over a field. Images are collected using an 8-12 μm IR detector mounted in a helicopter. The buried mines show up as light, circular images in the scene, and were identified as mines. The WES images clearly show that detection of the buried mines is possible based upon the thermal signature emitted from the overlaying soils.

2.2.5.2. Double-wavelength Thermal Detector

A two-wavelength thermal detector (both 3 to 5 µm and 8 to 12 µm) is currently being developed to replace the standard thermal detector. Using this technique has successfully detected ordnance buried at depths of 1" to 4". This two-channel IR scheme has no problems with the following terrain:

1. Cleared, level surfaces which include parking lots and grassy fields.
2. Vegetation-free terrain

2.2.5.3. Disadvantages of the IR Systems

Intense rain, snow or fog can render most IR sensors nearly useless at long ranges as illustrated Figure 2.2.5.4 with the 'fog' and 'drizzle' curves.

Limitations to the application of thermal IR sensors include range reduction during inclement weather. Furthermore, the following conditions may cause false detection due to "clutter" (i.e. confusing interpretation of data received from the IR radiometer): (1) variations in the soil composition, (2) variations in the temperature due to windy conditions and sources of shade, (3) variations in vegetation, (4) variations in the terrain (especially rough terrain), (5) subsurface water, and (6) buried rocks.

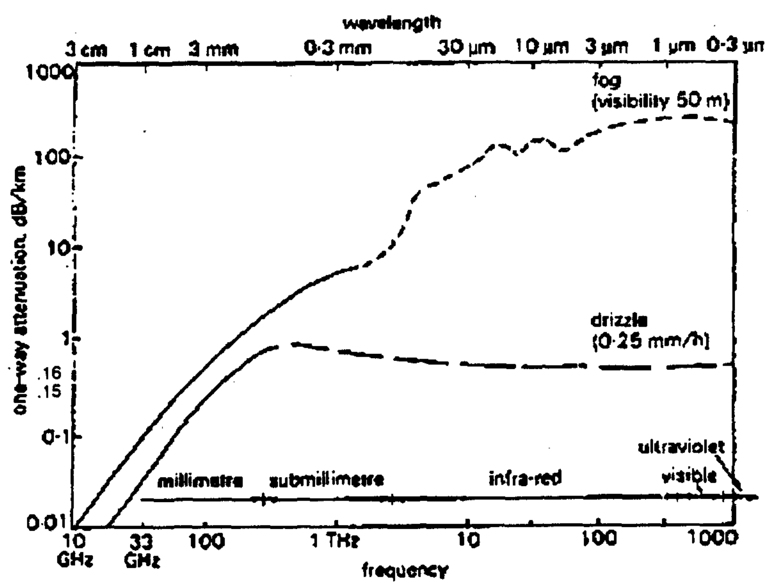


Figure 2.2.5.4. Attenuation of Electromagnetic Radiation as a Function of Wavelength

2.2.6. * LIDAR - 2D Imaging

There are several distinct laser remote sensing techniques. All are some form of laser radar known as LIDAR. Advantages of LIDAR include the ability to measure distant or inaccessible locations, negligible disturbance to the region by the measurement, near-real-time data availability, high spatial resolution, and rapid spatial survey in three dimensions. LIDAR has been used to obtain data such as gas composition, temperature, pressure, and wind velocity. Such measurements have been made for applications such as locating and identifying industrial smokestack emissions. Various types of LIDAR systems may be used to locate surface or underwater ordnance.

Two types of LIDAR measurement geometry can be used. Known as column and range-resolved measurement, the major distinction between the two is the target (see Figure 2.2.6.1.). In a column measurement, some type of hard reflective target, such as the ground or ocean surface, is used. Because all of the laser energy goes to the target and back, there is no direct range resolution; only the total column density along the measurement path can be measured. As a result, column measurements do not require a short laser pulse length. Because any hard target has a relatively high reflectance, efficiency is high and required laser energy is low.

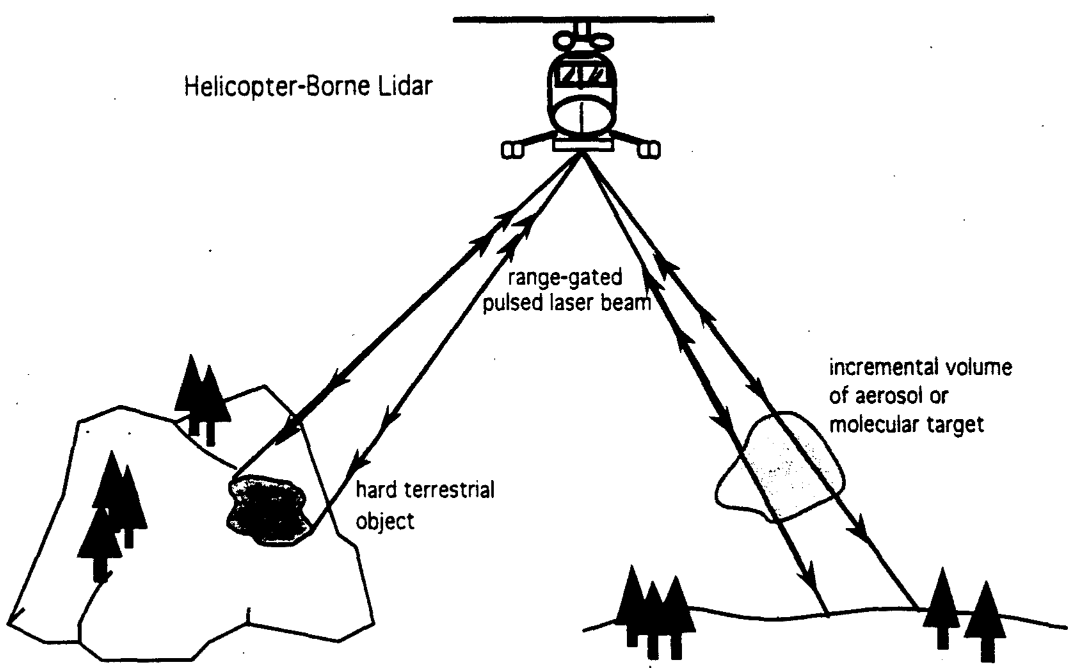


Figure 2.2.6.1 Column Measurement (left) versus Range-Resolved Measurement (right)

* This technology currently employed by the Corps of Engineers

In a range resolved measurement, the target is distributed, such as the atmosphere or ocean. Light is scattered volumetrically by the target itself. Measurements can be made by studying either the backscatter process or the effects of absorption along the route to and from the target. The delay time from laser pulse to receiver signal can be directly related to the range. Range resolution down to the laser-pulse length is possible.

Various methods may be used to obtain 2-D images of targets. Both polarimetric and underwater imaging LIDAR systems have demonstrated success in location of OEW.

2.2.6.1. Polarimetric LIDAR

Polarimetric LIDAR systems contain sensors that detect polarization changes in the backscattered energy obtained after illuminating the target with linearly polarized light. The vast majority of land mines have surfaces that are considerably smoother than naturally occurring backgrounds such as sand, soils, and short vegetation. This property is used to enhance separation from the background, which may provide an effective source of information for target detection. The U.S. Army has successfully demonstrated the REmote MInefield Detection System (REMIDS), which incorporates polarization and reflection data with thermal IR detector information to perform surface ordnance detection.

2.2.6.2. Underwater Imaging LIDAR

Underwater imaging LIDARs may be used for remote detection and imaging of underwater objects from an airborne platform. A system of this type is equipped with a green laser (Nd:YAG at 532 nm) which generates short pulses of light with pulse widths on the order of nanoseconds. Only lasers in the green to blue wavelength region provide water penetration. Other wavelengths are not used for imaging due to absorption of the laser light by water.

The laser beam is expanded by optics and projected down toward the surface of the water to an object or target. Intensified CCD (charge coupled device) cameras are electronically shuttered (range gated) after a time delay corresponding to the round trip propagation time to and from the target. This timing eliminates light scattered by the water from around the target. As a result, the veiling luminance of the water is greatly attenuated and faint target signatures can be seen. The resulting gated images (displayed on a CRT) have sufficient spatial resolution to classify and/or identify the target.

Targets may exist on the water bottom or be suspended above the bottom. "Floating" mines of this type were successfully detected using this technology during the Persian Gulf War. Although targets may be imaged in shallow, coastal and deep water, optimal conditions include calm, clear, or shallow waters. Water salinity does not affect image quality.

2.2.7. Biological Sensors

Trained canine/handler teams are extremely effective in their ability to detect explosive munitions via their olfactory sense. Explosive filler gives off an odor, which the dog detects through its acute sense of smell. They are also trained to detect and respond to visual clues such as metal or plastic casings, or trip wires to provide a more comprehensive search than with electronic odor detectors alone.

Dogs have demonstrated effectiveness in mine detection. During wartime, a dog platoon was used by US armed forces in South Vietnam with successful results. The dogs were used in a number of ways. Patrol missions were performed using the dogs to indicate both mines and booby traps. They were also used to perform a first sweep for mine detection over road areas.

The effectiveness of a dog handler team depends on terrain and weather conditions. Favorable conditions allow a dog to work a total of 5-6 hours per day, with resting periods every 1-2 hours. Overall forward speed may average 1 mile per hour. The distance a dog can be from an object in order to make a detection also varies with wind and terrain. Ideally, a dog placed downwind in a steady breeze may detect from distances of 300 feet. Conversely, upwind or cross-breeze conditions may require a distance of one foot. To avoid this, the animals may be repositioned and approach the site from a different direction. They may also detect items suspended up to 5 feet above ground, or almost 10 feet to the side of their constrained path.

To clear a strip area, the dog will typically move out at a trot, zig-zagging along the pathway. When presence of an explosive item is detected, they will stop about 2 feet away and sit. Although dogs may work on- or off-leash, they are most efficient when used off the leash. In this manner they can work up to 300 feet in front of their handler, even out of visual contact. Under such conditions, the dog may be equipped with a radio transmitter to allow the handler to recognize a sitting response by the dog.

The initial training of a dog takes approximately six months. Dog/handler teams must be kept in training in order to maintain skills.

Advantages to using dogs is that they can find a non-metallic mine which the metal detector overlooks and will ignore the metallic scrap that the metal detector senses. Also, dogs may be trained to incorporate visual clues to perform a more comprehensive search than by odor alone.

As explosives age, they emit decreasing amounts of odor. In an experiment where the explosives were buried 16 months prior, the dogs' ability to detect explosives was seriously impaired. Thus, as time passes these methods become less efficient at detecting OEW.

Once trained, dogs provide a quick and effective method for OEW detection. Rapid deployment of the dogs is essential to its effectiveness, as well as terrain and weather conditions.

Because the scope of this report is to evaluate manmade sensor technologies, the use of canines (and other scent-sensing animals such as pigs and rats) will not be included in the product summaries or comparisons.

2.2.8. Cone Penetrometer

Cone penetrometers are long rods, with a hardened cone tip, that are pushed up to 100 feet or more into the ground via a mechanism on a heavy truck that is capable of producing at least 10,000 pounds of thrust. Electronics in the cone tip relay data back to the surface. This information is collected and viewed onboard the truck, or held for later processing. Cone penetrometers have not been deployed for the purpose of detecting buried ordnance due to the possible danger of setting off the OEW during cone insertion into the ground.

Electronic measuring devices contained in the cone tip obtain data on subsurface pressure, resistivity, or water/soil analysis. Other available tip devices generate and receive electromagnetic waves, or measure seismic waves. Timing and intensity of these received or reflected waves indicate the density (and vector directions of) the surrounding soil. Older, entirely mechanical penetrometers exist, but most cone penetrometers today are electric.

Equipment usually consists of a penetration rod to which one of various probe tips are attached, depending on the type of measurement to be obtained. Some probes collect data in its final stationary position, and others collect continuously as it sinks into the ground. In this manner, vertical and/or horizontal profiling of an area may be performed. Currently, this technology is used to conduct geologic, water or soil sampling of an region. Probing techniques may be combined to one day locate subsurface ordnance. Various cone penetrometer capabilities are described below.

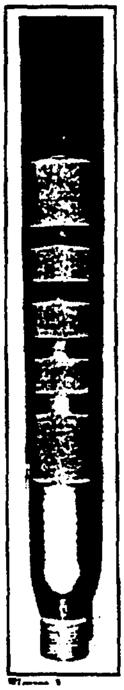
2.2.8.1. Test for Seismic Ground Waves

This consists of three-axis cones which can be used as a measurement device for surveys of the surrounding soil. Only a receiver is contained in the cone tip. Once the probe is stationary, a shock wave is hammered at the surface and the resulting waves received at the probe are evaluated (measured, recorded, etc.). The three-axis seismic cones or three-component motion sensor conducts seismic shear and compression wave surveys. These surveys may locate a buried object in the soil by examining the behavior of seismic/sound waves in an area. Seismic cone penetrometers may be used for measurements as deep as 270 feet in sandy soils.

2.2.8.2. Test for Resistivity

Resistivity, one of the oldest geophysical exploration techniques, was originally developed to locate minerals, oil deposits and ground water supplies. However, it may be of interest in the location of ordnance in the future. The measurement principle exploited by resistivity surveying is that an electrical contrast exists between different materials. The resistivity cone penetrometer has been used for contaminated site investigations to delineate the extent and degree of contamination at a site. These surveys rely on the resistivity contrasts that typically exist between contaminated soils and uncontaminated soils. Leachate from a landfill will contain a higher concentration of dissolved solids, which decreases the resistivity. Hydrocarbon-contaminated soils will have higher resistivity. As a result of the above findings, ordnance may be located by the difference in the resistivity measurements of the soil.

Figure 2.2.8.1 shows a resistivity cone penetrometer probe. The resistivity cone penetrometer probe is in intimate contact with the soil and core fluid which allows direct resistivity measurement of the media. The probe consists of four electrodes separated by five thicker plastic insulators. The outer two electrodes induce an electric current into the soil and the inner two electrodes measure the potential drop, which is proportional to the resistivity of the soil.



Source: Applied Research Associates

Figure 2.2.8.1 Resistivity Cone Penetrometer Probe

2.2.8.3. Other Types of Cone Penetrometer Probes

Several different kinds of probes are available for a cone penetrometer: Various probes are shown in the following three figures. Figure 2.2.8.2 illustrates groundwater and strata identification probes. Figure 2.2.8.3 shows the type of probe which takes soil, water or gas samples for chemical analysis.

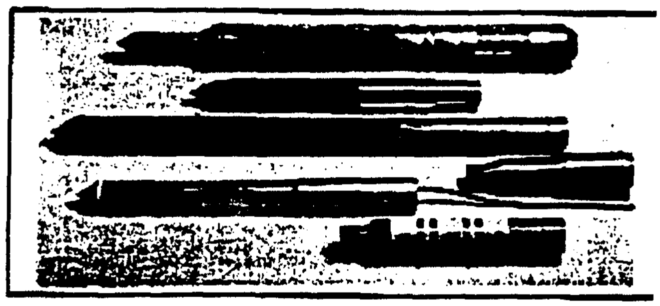


Figure 2.2.8.2 Exploration Probes for the Cone Penetrometer

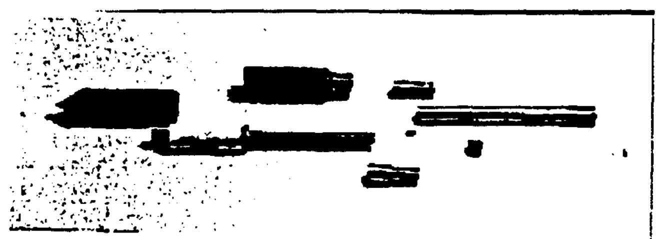


Figure 2.2.8.3 Sampling Probes for the Cone Penetrometer

A gamma radiation probe, shown in Figure 2.2.8,4, may be used to measure total radiation present and provide a spectrum of radiation that can be analyzed to determine the species and concentration of a contaminant. The Department of Energy (DoE) and Department of Defense (DoD) have a number of sites where radioactive materials have been accidentally leaked or buried underground and are in need of remediation. A system incorporating this technology has been used at the DoE's Hanford site to determine if a crib in which radioactive material had been deposited was leaking. In these situations it is important to find the leaks without exposing workers to the radioactive materials. Such a system can be used to determine the location of a waste canister or to determine the natural gamma radiation background.

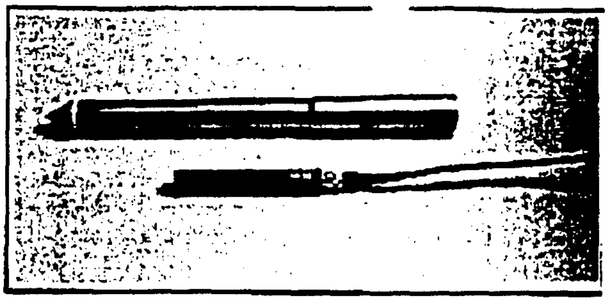


Figure 2.2.8.4 Gamma Radiation Probe for the Cone Penetrometer

2.2.8.4. Data Processing, Database Management, and Graphical Representation

For on-site characterization or ordnance location, assessment of probe data in real time is available. Most cone penetrometers that are available today have on-board data processing and graphics hardware to map out the site or location of ordnance. Alternatively, data may be stored on-board for later processing. Data systems are available providing horizontal or vertical profiling of an area, or even 3-dimensional rendering of a region.

2.2.8.5. Suitability for OEW Detection

The cone penetrometer is not recommended for the location of buried ordnance, since the penetrometer probe might accidentally detonate the UXO it is trying to detect (while pushing the rod into the earth). They are not better at detecting OEW than other sensors described in this document; they cannot distinguish between a rock and UXO, and their probing range from each penetrometer hole is limited.

The cone penetrometer's poor match for OEW detection was not discovered until research into method and vendors had already begun. Rather than remove the information already collected, the section describing cone penetrometer vendors (Section 4.1.4) was left as-is and no attempt to prepare an exhaustive list was made.

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2.3. EMERGING SENSOR TECHNOLOGIES

Recent developments in sensor technologies promise a new generation of detectors that are more sensitive and can survey large sites using fewer resources and in less time than the current techniques. The term "emerging technologies" refers to technology that is not currently available off-the-shelf; it is a promising technology that exists in the laboratory or field-proven stage and has not yet been commercially deployed.

This section provides a summary of promising technologies that could improve the process of OEW detection. These technologies along with their developers and/or manufacturers where available appear in Section 4.2, Emerging Sensor Technology Products.

2.3.1. Magnetometers

Three promising improvements to conventional magnetometers are presented below. Three-axis fluxgate magnetometers provide improvements over the single-axis fluxgates described in Section 2.2.1.3; and the Overhauser Effect is an improvement to the Proton Precession Magnetometer described in Section 2.2.1.1. The electron tunneling magnetometer (Section 2.3.1.3) is a new microsensor that can be manufactured using integrated circuit processes.

2.3.1.1. Three-Axis Fluxgates

The primary advantage of using a 3-axis magnetometer is its unique capability of locating ferrous metallic objects by measuring both the direction and the distance (range) to the metallic object.

The directional component can be obtained directly, since a 3-axis magnetometer measures the magnetic field in three orthogonal directions. The magnetic field vector intensity pinpoints the direction from the source to the measured ferrous metallic object.

The distance information can be inferred by combining measurements from both a magnetometer and a gradiometer. The magnetic field strength as measured by the magnetometer is defined as

$$T = \frac{2kFV}{r^3}$$

where

T	is the peak total field anomaly measured in γ
k	is the volume magnetic susceptibility of steel (a unitless characteristic)
F	is the magnetic field strength, in nT
V	is the volume of the sphere in cubic meters, and
r	is the distance between the source and sensor in meters.

The gradient peak vertical magnetic field intensity ("Vertical Gradient", or "VG") measured by the gradiometer is given by the first derivative of T, which is

$$VG = \frac{6kFV}{r^4}$$

Dividing the magnetometer results by the gradiometer results yields the distance directly:

$$\frac{T}{VG} = \frac{\frac{2kFV}{r^3}}{\frac{6kFV}{r^4}} = \frac{r}{3}$$

Thus, the distance r can be inferred by dividing the magnetometer reading by the gradiometer reading. Since a gradiometer is simply a pair of sensors separated by a known distance, all one needs is a 3-axis sensor plus a one axis sensor at a fixed distance to obtain the vector pointing to the buried metallic substance.

2.3.1.2. Overhauser Effect

A new enhancement to proton precession magnetometers is called, "The Overhauser Effect." In this scheme, an electron-rich fluid (containing free radicals) is added to a standard hydrogen-rich fluid. This mixture increases the polarization by a factor of 5000 in comparison with standard liquids. In contrast to conventional proton precession methods, Overhauser proton precession uses a radio frequency (RF) magnetic field, and uses a fraction of a Watt of RF power, rather than a high-power direct current (DC) field.

Overhauser magnetic systems maximize resolution and minimize power consumption. Another advantage is that proton polarization and measurement can occur simultaneously, so the system response time is much faster. (A proton-precession magnetometer's integration time can be on the order of seconds, as opposed to fractions of a second for the Overhauser Effect.)

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2.3.1.3. Electron Tunneling Magnetometer

In 1982, a new surface microscopy was invented at IBM Zurich. This enabling technology used quantum mechanical tunneling of electrons across a narrow barrier to measure separation with unprecedented sensitivity. As shown in Figure 2.3.1.1, a microscopically small electrode tip is placed very close to the surface. As bias voltage is applied between this tip and the surface, electrons will tunnel across this barrier. This tunneling current is proportional to the distance between the tip and the surface. This relationship is shown in the figure, where I is the tunneling current, V is the biasing voltage, and S is the microscopically small separation, measured in Ångstroms (Å). Thus, by closely monitoring the tunneling current, extremely accurate measurement (as low as 10 Å) of the separation can be measured.

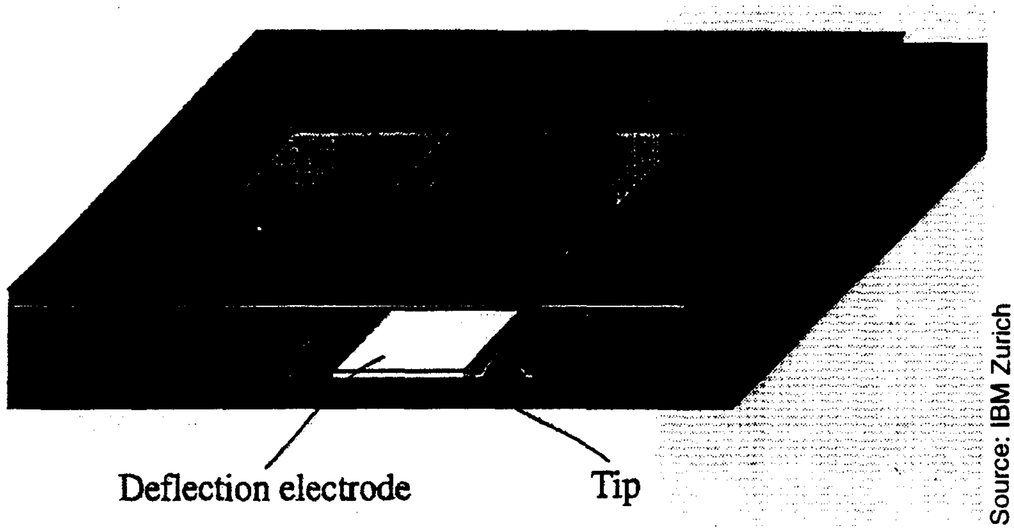
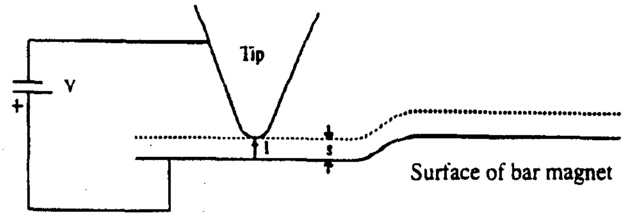


Figure 2.3.1.1 Electron Tunneling Sensor



$$I \propto Ve^{-\alpha\sqrt{\Phi}s}$$

Figure 2.3.1.2 Electron Tunneling Sensor (schematic)

The schematic diagram of an electron tunneling magnetometer is shown in Figure 2.3.1.2. This magnetometer consists of a bar magnet placed in parallel with a deflection electrode, which appears as the solid and dotted lines of the bar magnet surface. A tunneling sensor tip is fabricated at the side of the deflection electrode. When this magnetometer is placed in an external magnetic field, the bar magnet will be moved by this field and therefore alter the fine spacing between this bar magnet and the deflection electrode. This minute variation in spacing will in turn vary the tunneling current. A feedback biasing voltage is applied between the tunneling tip (connected together with the deflection electrode) and the bar magnet. This feedback biasing circuitry is designed such that when the bar magnet moves with the external magnetic field, a feedback voltage is generated to inversely move the deflection electrode to maintain a constant spacing. As a result, the variation in feedback biasing voltage is a precise measurement of the external magnetic field. The sensitivity of this type of electron tunneling magnetometer is as high as 0.001 gamma.

Many different sensors have been developed using this technology, including magnetometers, accelerometers, uncooled IR sensors and seismometers.

2.3.1.4. Fiber-Optic Magnetometers

An important advantage of fiber-optic magnetometers is their ability to provide passive sensing of a wide range of physical fields. This not only means that the sensor head operates without the need for electrical power, but also that the overall system (including the input-output fibers that serve as the telemetry links) is electrically passive, and thus the whole system exhibits a low intrinsic susceptibility to the effects of electromagnetic interference (EMI) and electromagnetic pulse (EMP). These issues are important when a sensor is required for use in explosively hazardous or electrically noisy environments. By servicing a number of fiber sensors using common input and output fiber links, an all-fiber sensor network can be formed that has additional advantages to those outlined above. Moreover, due to the extremely light weight and flexibility in system design of this fiber-optic magnetometer, it can be integrated into a hand-held portable system for site characterization use.

A magnetostrictive fiber-optic magnetometer employs a fiber Mach-Zehnder interferometer to measure the magnetic-field-dependent strain (magnetostriction) in a transducing material. A basic fiber-optic Mach-Zehnder interferometer is illustrated in Figure 2.3.1.3. In this figure, a coherent single-mode laser source on the left is launched into the single-mode fiber. The light is then split into two beams of equal intensity by a fiber-optic beamsplitter (called a "coupler" in the diagram), splitting the beam into the sensing fiber coil (L1) and the fiber reference coil (L2). After passing through the sensing and reference fiber coils, these two signals are recombined by the second fiber beamsplitter ("coupler") on the right. An interference signal between the two beams appears at the coupler's outputs which, after propagating the length of the output fiber, is detected by the photodetectors. It should be noted that this form of sensor may be operated with a large length of fiber (> 10 km) between the detector module and the sensing interferometer while still maintaining high performance.

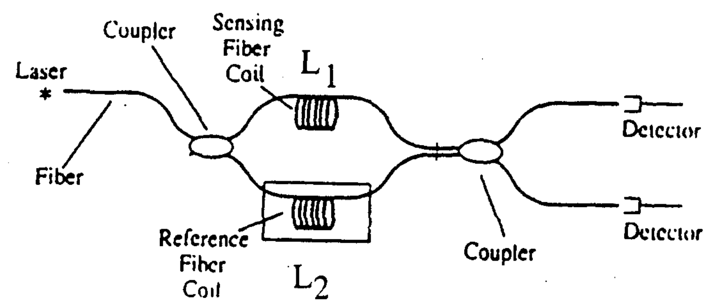


Figure 2.3.1.3 Schematic of a fiber-optic Mach-Zehnder interferometer

A basic schematic diagram of a fiber-optic magnetometer is shown in Figure 2.3.1.4. In this figure, a magnetostrictive material is bounded to one arm of the interferometer. When an external magnetic field exists, this field will generate a strain to the sensing arm of the fiber interferometer. A field-dependent phase shift will be induced in this interferometer and could be detected by the output detector. This phase shift is proportional to the intensity of the external magnetic field and can be effectively measured.

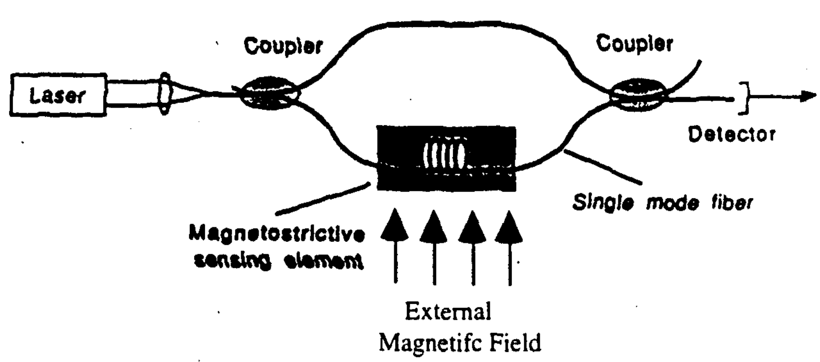


Figure 2.3.1.4 System schematic diagram of a magnetostrictive fiber-optic magnetometer employing a Mach-Zehnder interferometer

Two basic types of optic magnetostrictive transducers are shown in Figure 2.3.1.5.. In the first type, the fiber is jacketed with a magnetostrictive material, either over bare fiber or over fiber already jacketed with a nonmagnetic polymer, yielding a continuous length of magnetically "sensitive" fiber. In transducers of the second type, the geometry of the magnetostrictive material is fixed and a length of fiber is bonded to the material. Flat rectangular strips and cylinders are the most common geometries.

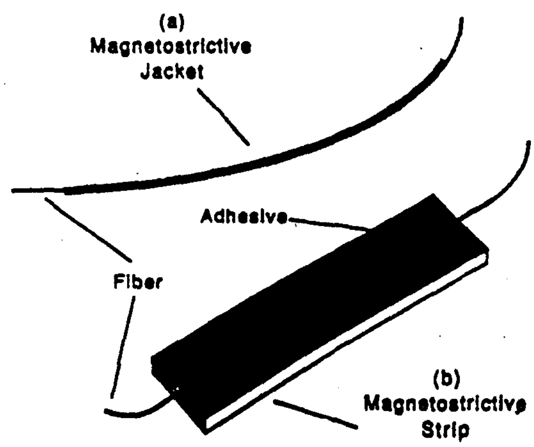


Figure 2.3.1.5 Two types of magnetostrictive transducer: (a) magnetostrictive jacket on fiber; (b) fiber bonded to magnetostrictive element

By using three Mach-Zehnder interferometers, a 3-axis fiber-optic magnetometer or gradiometer could easily be built which could be used to simultaneously measure the magnetic fields in the x, y, and z directions. Furthermore, the entire system could be powered by a single laser source. The typical sensitivity of this fiber-optic sensor is 0.1 gamma.

Fiber-optic magnetometers are completely immune to electromagnetic interference, since there are no conductive wires that might induce a current in the presence of electromagnetic (EM) noise. If one were to also employ fiber optic cables between the sensor and the processing electronics, extremely remote sensing can occur while still maintaining high data quality. (When remote sensors are connected using long wires, the same EM susceptibility exists and the signal quality will be degraded, usually in proportion to the length of the wire. Fiber optic cables are immune to such interference and have negligible signal loss compared to metal wires.) Thus, an all-fiber-optic sensor, such as a fiber-optic magnetometer connected using fiber-optic cables, is ideal for remote sensing applications where the long wires would otherwise degrade the signal, such as in underwater applications.

2.3.2. Electromagnetic Induction - AC Susceptibility

Alternating current (AC) susceptibility works on the principle that most items will become partially magnetized when exposed to a magnetic field. The amount of magnetization retained varies for each substance, and therefore can be employed as an identification signature.

This technique shares the same limitations as proton precession magnetometers, since they both work on the same principle. The only difference is that AC susceptibility employs magnetic signature identification, telling the operator not only that an object has been detected, but what the object most likely is.

Currently this technology remains a theory, and only one company has been uncovered that thinks it can successfully implement one. (Refer to Section 4.2.2 for more information.)

2.3.3. Ground Penetrating Radar

This section describes the new, emerging GPR techniques which are currently in the laboratory or prototype stage. For a tutorial on GPR foundations, refer to Section 2.2.3.

2.3.3.1. Harmonic Radar

Harmonic radar, a type of ground-penetrating radar, combines favorable aspects of synthetic-aperture radar (SAR) and metallic radiation characteristics to enable metallic OEW detection. It is performed aerially over the area of interest.

It has been observed for many years that illuminating metallic objects with high-power microwaves generates re-radiation at harmonic frequencies. The source of the regeneration of these harmonic frequencies (usually at the third harmonic, or three times the frequency of the illuminating signal) is the joints of the metal surfaces; when these surfaces are in close proximity, they form semiconductor-like junctions. These junctions radiate harmonics when illuminated by microwaves.

It has also been known that low frequency microwaves penetrate ground relatively well (this forms the theoretical basis for ground-penetrating radar). The harmonic regeneration phenomenology, when incorporated into a GPR, can allow easier detection of surface and buried metallic ordnance, acquiring a signal largely devoid of clutter from rocks and non-metallic debris.

In use, the harmonic radar illuminates the ground with low-frequency waves generated from a radar transmitter, and receives the back-scattered waves at the third harmonic frequency. Since the third-harmonic returned waves are generated only from metallic objects, the harmonic radar is capable of rejecting strong surface reflection as well as reflection from other nonmetallic objects.

The primary disadvantages of harmonic radar include the requirement for high ground incident power densities that leads to high transmitter power and/or short operating ranges, limited to a few kilometers. Plus, metallic joints must be plentiful and large enough to be identified; a smooth metallic sphere buried in the ground would not be detected using this technique. In general, this technique is best used for finding clusters of large metallic objects such as tanks, jeeps, and stationary aircraft, and does not appear applicable for detection of small objects such as ordnance.

2.3.3.2. Interferometric Impulse Radar

Interferometric impulse radar is a new generation of ground penetrating radar that offers an alternative to standard GPR and the SAR. Unlike conventional SAR, the interferometric radar takes a snapshot of the underlying terrain by observing the interference pattern reflected by the targets. Using a process similar to image reconstruction in optical holograms or medical ultrasound, the reconstructed 3-D image shows the shape, size and depth of the buried objects. This process is different from that of the SAR, which uses a continuous sweeping operation to acquire the necessary information to plot a similar 3-D buried object map.

An interferometric radar consists of a transmitter (impulse source and antenna), multiple receivers, control electronics, and data processing hardware/software. The transmitter antenna generates a wide beam that is able to cover a large area. Each of the multiple receivers (3 or more) are separated by a distance equivalent to several pulse widths.

In operation, the transmitter antenna generates a narrow-width pulse train to probe the ground. The reflection from the terrain surface returns first, and serves as the reference signal. Buried objects (as well as surface objects) will also reflect the probing beam and be received by the multiple receivers a few milliseconds later. The time delay between the reference signals and the object signals received by each of the multiple receivers provides enough interferometric data to reconstruct a 3-D image.

The resolution of an interferometric radar is estimated to be at 1/3 of the wavelength in the soil under measurement. Smaller objects could be detected with this technique, but would not be identifiable.

2.3.3.3. Stepped FM

As the name implies, stepped FM is a rapid sequence of impulse radar pulses generated at increasing (or decreasing) center frequencies. Since different probing frequencies result in different penetration depths and resolutions, a stepped FM system can be viewed as a miniature data fusion system combining images from multiple radar frequencies into higher-quality output.

A stepped FM GPR is a computer-based instrument which relies heavily on digital signal processing. The system measures the amplitude and phase angle at each probing frequency, and performs a Fourier transform on it to translate the signal from the frequency domain back into the time domain, resulting in an output similar to that of an impulse-style radar.

(Stepped FM should not be confused with FM-CW radar (which is all analog), although the benefits are similar.)

2.3.4. Visible Imaging

2.3.4.1. Charge-Coupled Devices (CCDs)

Charge-coupled devices (CCDs) are being used extensively in today's electronic cameras and are considered to be state-of-the-art. However, a new technology, the active pixel sensor (APS), might be a successor to CCD. This technology potentially features the same sensitivity and performance of the CCD, but with additional improvements. These improvements include random access capability, easy window-of-interest readout, non-destructive readout for signal-to-noise improvement, high radiation tolerance, simplified clocking voltages, and easy integration with other on-chip signal processing circuitry.

A simple example of an active pixel is illustrated in Figure 2.3.4.1. In this example, an active pixel sensor (APS) structure that resembles a short CCD is shown. Charge is integrated under the photogate PG. To read out the signal, the pixel is selected using transistor S. The output node is reset using transistor R. The signal charge is then transferred from under PG into the output node. The change in the source follower voltage between the reset level and final level is the output signal from the pixel. The source follower might drive a column line terminated with clamp and/or sample-hold circuits. These column-parallel circuits can then be scanned for serial readout of the sensor. Since the illustrated APS requires only a single intra-pixel charge transfer, many of the problems associated with charge transfer with CCDs are eliminated.

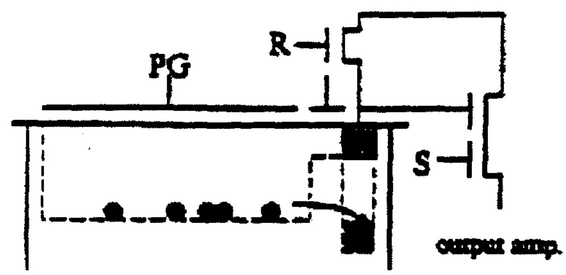


Figure 2.3.4.1 Schematic of an active pixel sensor (APS)

2.3.4.2. Spatial Resolution And Swath Width Evaluation Of An Airborne Imaging Sensor

Airborne imaging sensors, including various infrared, visible systems and LIDAR systems, consist of a telescopic imaging lens and a focal plane array image detector. The spatial resolution of these type of sensors depend upon the selection of focal length of the imaging lens, the pixel size of the focal plane array, and the altitude of the airborne platform. A system diagram appears in Figure 2.3.4.2.

According to Newton's lens law, when the terrain image is recorded at a distance much longer than the lens' focal length, the image is focused at the back focal plane of the lens. When a focal plane array (IR or CCD) is placed at the back focal plane to record the demagnified terrain image, the demagnification factor M is :

$$M = (\text{focal length / platform altitude}) = f / h$$

The ground pixel size L recorded by a corresponding pixel in the focal plane array is therefore:

$$L = (\text{focal plane array pixel size / demagnification factor}) = d / M = (dh) / f$$

Furthermore, the swath width SW covered within the field of view of this airborne array is

$$SW = \text{ground pixel size x total number of pixels} = L \times N$$

Example

An airborne imaging sensor, flown at an altitude of 10,000 meters, utilizes a 100 mm (10^{-1} meter) lens and a 128 x 128 focal plane array. The pixel size of this array is 200 μm (2×10^{-4} meters). The ground pixel size is therefore:

$$L = (dh) / f = (2 \times 10^{-4}) \times 10^{4} / (10^{-1}) = 20 \text{ meters}$$

The corresponding swath width is

$$SW = 20 \times 128 = 2{,}560 \text{ meters}$$

The terrain resolution could easily be altered by using different imaging lens focal length and different size of focal plane array. The spatial resolution and swath width are also linearly variable with the flight altitude.

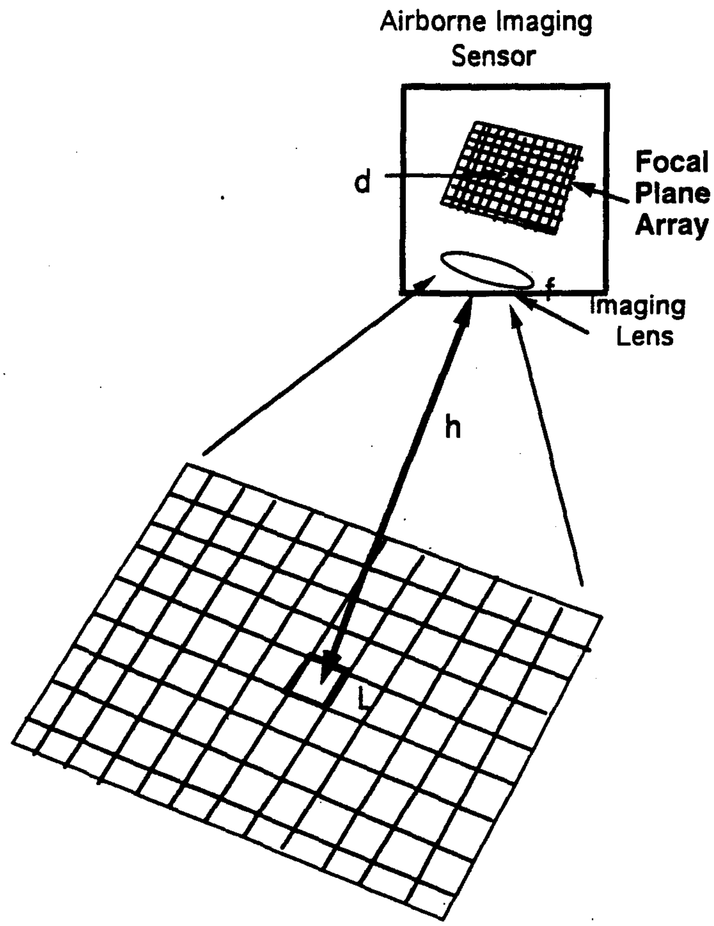


Figure 2.3.4.2. System Schematic Diagram Illustrating The Spatial Resolution And Swath Width Seen By An Airborne Imaging Sensor With A Focal Plane Array.

2.3.5. Infrared (IR) Spectrometry

When the detection of infrared radiation is divided into more than three subdivisions, the detection technique is known as infrared spectrometry. Infrared spectrometry often combines the short-wave IR band (1-3 microns in wavelength), mid-wave IR band (3-7 microns), and the thermal IR band (7-15 microns). This can be accomplished by using a number of narrow-band filters having spectral transmittances at differing wavelengths within the band. Alternately, spectral discriminators such as prisms and diffraction gratings can be used to disperse the energy at the focal plane of the optical system such that various wavelengths can be individually examined (see Figure 2.3.5.1). If only selected wavelengths are measured, the spectrometry is referred to as "multi-spectral"; if wide-range contiguous samples are taken, the terminology "hyper-spectral" is frequently used.

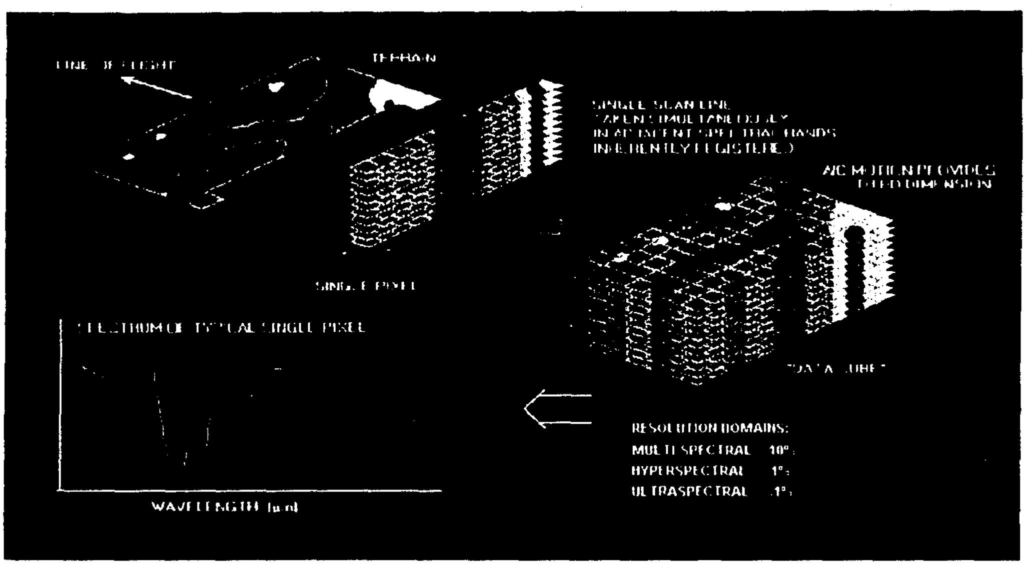


Figure 2.3.5.1 The Spectrometric Data Cube

Infrared imagers (also known as imaging spectrometers) sensitive to two or more infrared bands are being developed with the capabilities of multi- or hyper-spectral radiometers and the additional capability of being able to provide correlation of the radiance data with specific locations in the target scene. Instrumentation with all of the diverse capabilities described above is being developed or is in use utilizing detectors having sensitivities in the near-, short wave-, mid-wave, and thermal infrared bands.

Unconfined explosives frequently outgas volatile constituents into the atmosphere. If these chemical compounds lie on or near the surface, the gases can be readily detected with infrared spectrometry in most of the IR bands by detecting the unique absorption signatures of the compounds (frequently ammonium nitrates). The effectiveness of this technique is limited to searches made relatively soon after explosives are exposed.

Although the infrared sensors perform their tasks very well, they are not as well-suited to detecting OEW as a sensor with ground-penetrating capability, such as GPR or electromagnetic induction sensors.

A great advantage to the infrared detector is that they readily lend themselves to fabrication in line and area array configurations. This has permitted the implementation of compact and rugged imagers and imaging spectrometers. The element-to-element uniformity achievable when all elements are fabricated simultaneously, plus the elimination of scanning mechanisms has led to the acceptance of this type of equipment throughout the IR industry.

The currently available imaging spectrometers are intended for air- and space-borne applications. The data acquisition involves transiting the area under survey to develop an extended spatial image. Area array detectors "push broom" the projection of one detector line down the vehicle track, generating a swath of ground coverage. (For an explanation of swath width calculations, refer to Section 2.3.4.2.) Line array detectors require an additional "whisk-broom" provided by a cross-track scanning mirror.

Imaging spectrometers available today cover the visible, NIR (near infra-red) and SWIR (short-wave infrared) spectral bands. New spectral discriminator developments coupled with detector improvements are approaching marketability. Fast Fourier Transform (FFT) spectrometers have emerged from the laboratory and are being marketed.

Imaging spectropolarimeters are being developed using acoustic-optical tunable filters (AOTF's). This form of instrumentation does not require instrument motion or mechanical scanners and can be made to operate in the SWIR and MWIR bands as well as the visible. New diffractive (binary) optics and variable filters (circular and linear) will also be able to provide the full-frame form of spectral imaging. A valuable feature of these techniques is "spectral agility", allowing users to restrict operation and data acquisition to only those wavelengths known to be of interest. High-speed FFT spectrometers are being implemented operating in imaging mode. While still quite slow at acquiring a broad-coverage image. in comparison to grating and particularly full-frame, FFT spectrometers can provide extremely high (better than 1.0 nanometer) spectral resolution.

2.3.6. Millimeter-Wave (MMW) Radiometry

Millimeter Wave (MMW) radiometry uses the same principles as infrared (IR) radiometry. A temperature map is created by measuring the thermal emittance of the terrain. The difference is the thermal emittance is measured in the millimeter

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frequency range for MMW radiometry, as opposed to the infrared frequency range for IR radiometry. MMW radiometers operate at wavelengths below that of the submillimeter band edge at 1000 μm (1×10^{-3} m) as shown in Figure 2.3.6.1.

Given the temperature map of the terrain, foreign objects, buried or otherwise, will show up as temperature differences from the normal background temperature. Like other thermal imaging techniques, MMW radiometry does not work well when the background terrain conditions are not uniform. Thus, we will focus on the differences between IR radiometry and MMW radiometry in the remainder of this section.

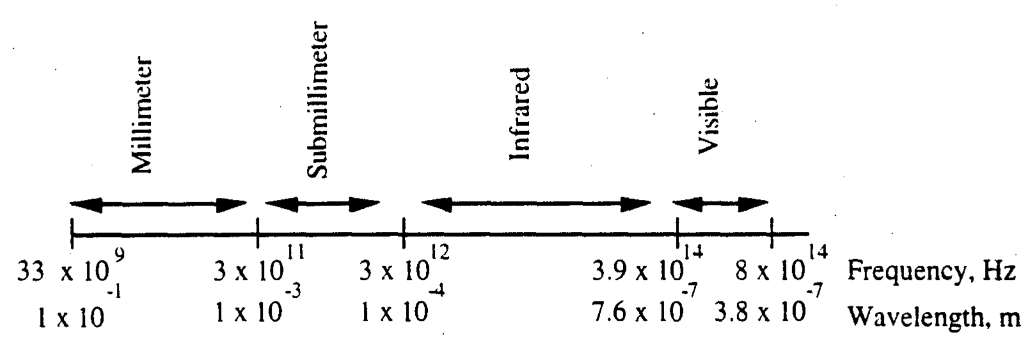

Figure 2.3.6.1 The Electromagnetic Spectrum.

Weather conditions that can seriously restrict IR radiometers have minimal effects on MMW radiometers. MMW does not suffer from attenuation problems under cloudy or drizzly conditions as shown in Figure 2.3.6.2. As shown in the figure, MMW radiation will be attenuated by 0.1 dB/km in drizzly conditions, and 0.15 dB/km under foggy conditions. By comparison, IR radiation is strongly affected, incurring attenuation of 0.16 dB/km under drizzly conditions, and 100 dB/km during foggy conditions.

A disadvantage of MMW radiometry is that the target has a much lower thermal emittance in the millimeter wave spectrum as opposed to the IR spectrum. This is illustrated in Figure 2.3.6.3, where at 320K, the thermal emittance is 9 orders of magnitude more in the infrared range compared to the millimeter range. Overall, the net effect is that IR radiometry and MMW radiometry have very similar thermal sensitivities.

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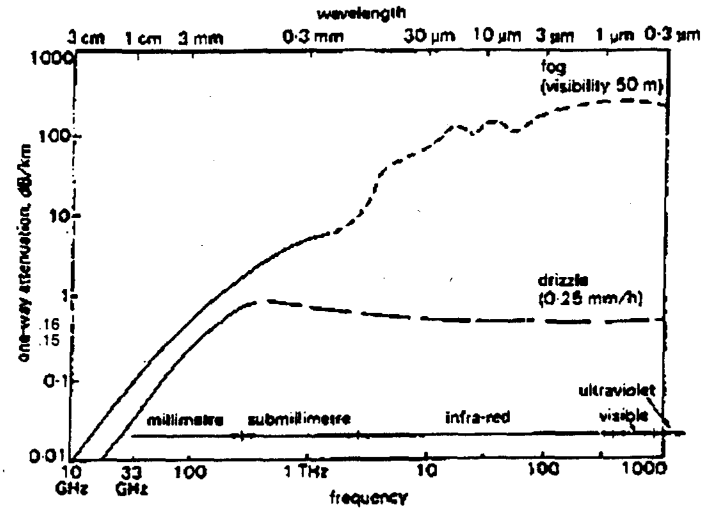


Figure 2.3.6.2 Attenuation vs. Frequency and Weather Conditions.

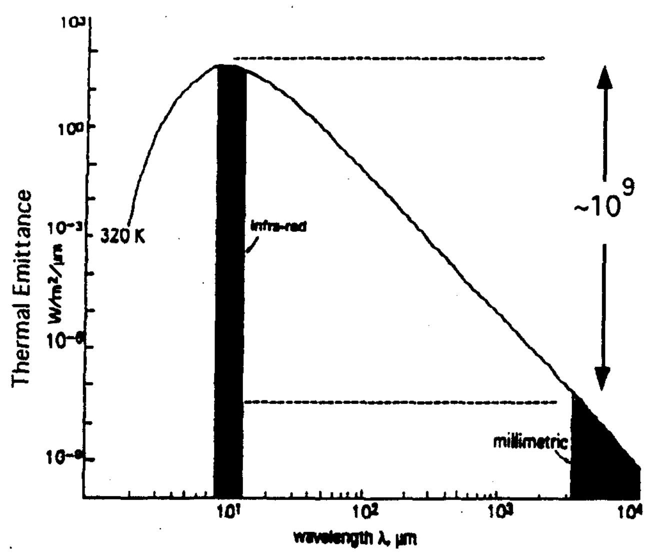


Figure 2.3.6.3 Thermal Emittance vs. Wavelengths

Figures 2.3.6.4 and 2.3.6.5 show some results of using MMW radiometry. Figure 2.3.6.4 shows the visible image and the corresponding MMW image on a clear day. Figure 2.3.6.5 is the identical scene except under foggy conditions. Note that performance of the MMW technique is quite good even under poor weather conditions.

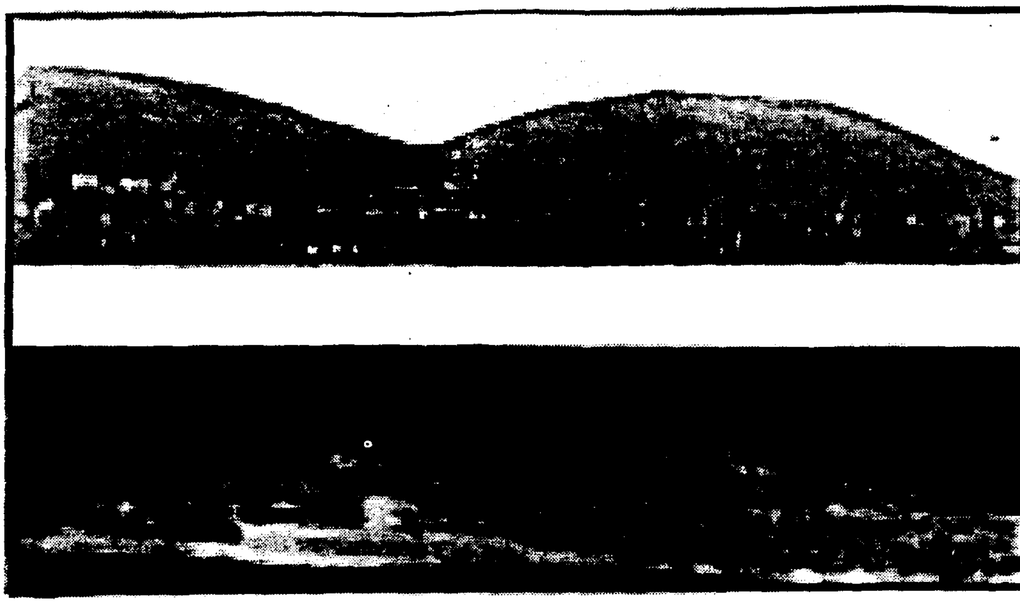
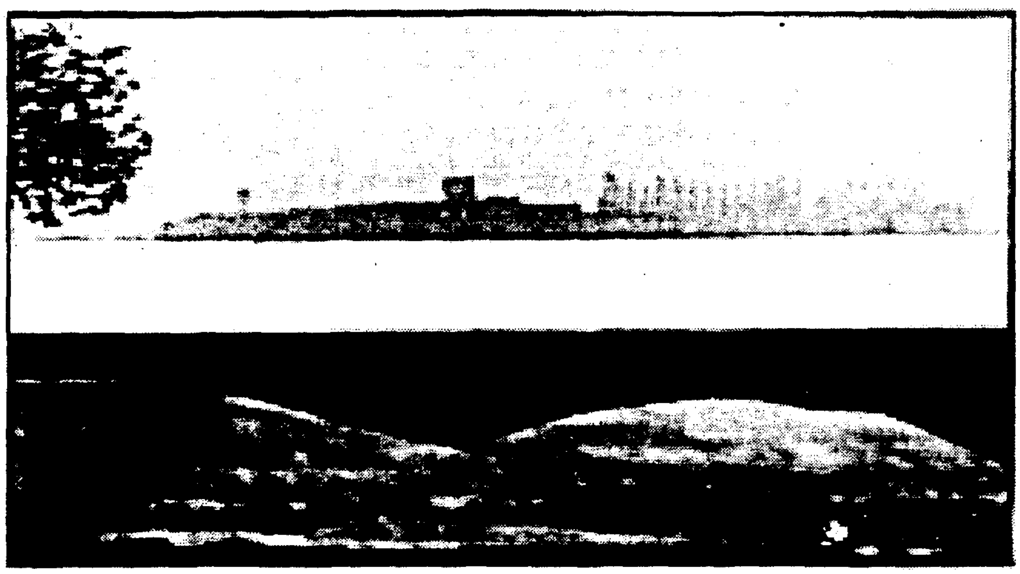


Figure 2.3.6.4 Visible (top) and 94 GHz millimetric (bottom) images on a clear day



Source: Optical Engineering Magazine

Figure 2.3.6.5 Visible (top) and 94 GHz millimetric (bottom) images on a foggy day.

Difficulties encountered with MMW result from the considerably reduced (10^{-6}) radiant emittance of the Earth at these wavelengths, and the diffraction limit on resolution requiring large apertures to achieve usable results similarly to those needed for SAR imaging. Nonetheless, the ability to detect the temperature

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anomalies indicative of OEW through inclement weather can make this approach attractive for certain specific applications.

Single-channel radiometry cannot image in real time. The solution is to have an array of channels that are scanned, either mechanically or electronically. Such imaging MMW radiometry techniques are being investigated. The present systems view a scene by scanning the antenna in a raster pattern. In a manner similar to that used for the single element-detector IR imaging radiometer, the image is built up over time as a collection of single point intensities corresponding to pixels in the resulting picture. Integration times of 10 msec per position establishes a "frame" time of approximately half an hour for a 400 X 400 element picture. Additionally, the spatial resolution is a direct function of the aperture; a 1-meter diameter antenna will provide approximately a 3 millirad instantaneous field-of-view (IFOV). To improve on this situation, multi-aperture, multi-channel systems are being developed that will operate in a manner analogous to the IR array detector.

2.3.7. LIDAR - 3D Imaging Systems

Various methods may be employed to obtain 3-D backscattered images of targets. Although not previously used for detection of OEW, 3-D LIDAR may be a candidate for further investigation. Subsurface OEW may be indirectly detected by sensing for specific chemical vapors or liquids escaping from emplaced munitions. Upon reaching surface terrain, these chemicals may be detected.

2.3.7.1 Laser-Induced Fluorescence LIDAR

Laser-induced fluorescence (LIF) LIDARs use the gas species being measured as the target and are therefore intrinsically range resolved. Molecules absorb laser radiation on an atomic or molecular resonance and re-emit (or fluoresce) generally at a longer wavelength. The backscatter and the measurement processes are the same. The fluorescence is selectively detected at the emission wavelength.

Line spectra LIDAR, a type of LIF, has been used to perform spectral fingerprinting. Such systems sense chemical fluorescence from an airborne platform to identify gas, crude oil, and fuel in a slick on the sea surface. These systems have also been to identify presence of subsurface pollutants in water strata by measuring dissolved organic matter.

2.3.7.2 Raman LIDAR

Raman LIDARs are very similar to LIF LIDARs; however, the backscattering mechanism is different. Because no actual molecular resonance is used for absorption, a major advantage of Raman LIDAR is the possibility of using fixed-frequency lasers. Species are selected by tuning the receiver rather than tuning the laser. Raman spectroscopy represents a particularly powerful tool for laser remote sensing because it enables a trace constituent to be both identified and quantified relative to the major constituents of a mixture. Because of the low Raman-scattering cross sections, return-signal levels are generally low. This tends to limit the range, sensitivity, and daylight operation of these LIDARs.

2.3.7.3 Aerosol Measurement LIDAR

Aerosol measurement LIDARs detect atmospheric gases by simple backscatter using fixed-frequency lasers. A single measurement, however, cannot distinguish between aerosol density and aerosol size. The measurement can be enhanced by using several widely spaced wavelengths, such as the multiple harmonics of a Nd:YAG laser.

2.3.7.4 Differential Absorption LIDAR

DIfferential Absorption LIDAR (DIAL) may perform both column and range-resolved measurements using hard or atmospheric aerosol targets, respectively. Tunable lasers are required for most DIAL measurements, as the wavelengths must be matched to specific molecular absorptions. Range-resolution measurements relate directly to delay time between a laser pulse and the received signal. As shown in Figure 2.3.7.2, the shaded portion under the curve corresponds to signal differences due to absorption of the laser beam by gas existing between R and ΔR. The boundary of the gas is the limit of the measurement. Column measurements may be obtained by sending laser light at several wavelengths or at a single scanned wavelength to a target.

The variation of round-trip absorption with wavelength is a measure of the molecular absorption along the path, and hence the molecular density. For example, two nearly equal wavelengths may be chosen that have a large difference in absorption by the gas of interest (see Figure 2.3.7.3). Use of nearly equal wavelengths minimizes other wavelength-related variations in the system. From the ratio between the two measured absorptions, "on" and "off", the type and density of the gas may be determined.

DIAL systems have been developed for chemical vapor measurement. A carbon dioxide laser with multi-spectral lines around 10.6 micrometers is the most suitable DIAL system for such measurements, as most chemical vapors have rich absorptions in the 9 - 11 micrometer spectral range. Such a DIAL system has been developed by both the U.S. Army Chemical Research, Development and Engineering Center and by SRI and U.S. Army Dugway Proving Ground. In addition, the Army Research Laboratory is also engaged in carbon dioxide DIAL system development.

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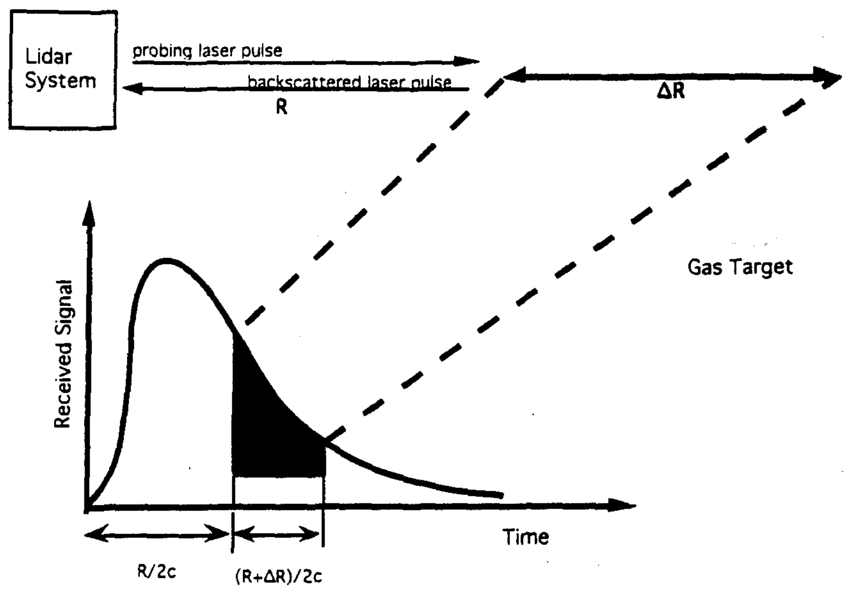

Figure 2.3.7.2. Range Resolution Measurements Relate Directly to Delay Time Between Laser Pulse and Received Signal

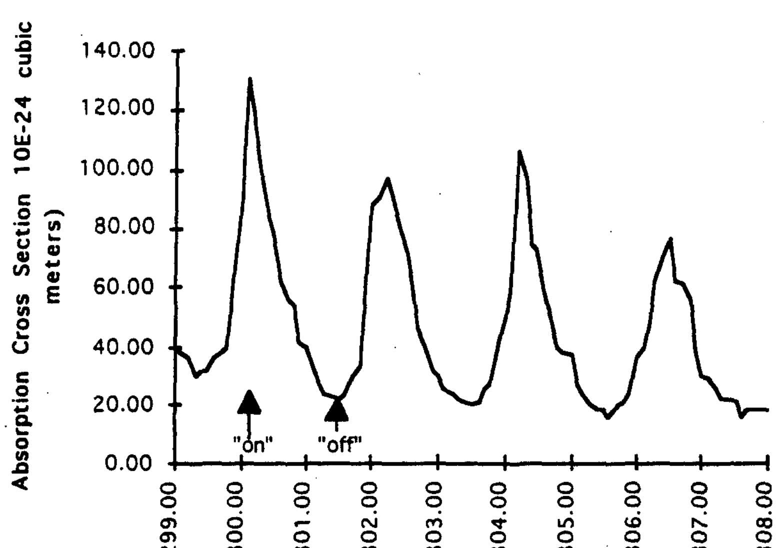

Figure 2.3.7.3. Chemical Identification Using DIAL by Measuring the Differential Absorption Ratio

2.3.8. Nuclear Technology

Nuclear technology exploits the fact that the elemental composition of explosive objects differs significantly from its surrounding environment. A key characteristic of explosive compounds is the presence of large amounts of nitrogen, hydrogen, and oxygen. For example, the nitrogen mass fraction in explosives is typically at least 18.5% or higher. In contrast, nitrogen is almost negligible in natural soils. Nuclear technology involves illuminating an area with a radiation source, which excites one of the elements in an object. The element then emits a unique signature which can be detected.

The ideal set-up for detecting an object is to have the object appear between the source and the detector as illustrated in Figure 2.3.8.1; however, this is impractical and unlikely for OEW detection. Hence, only backscatter detectors which detects the scattering can be used as shown in Figure 2.3.8.2.

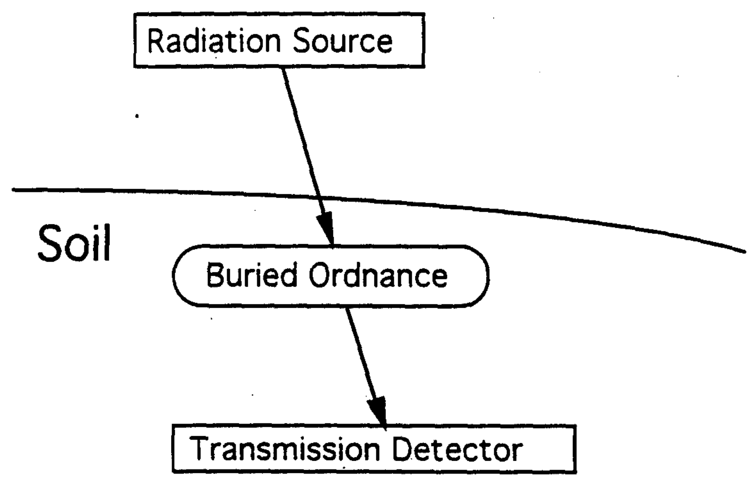

Figure 2.3.8.1 Non-Feasible Technique of Placing the Transmission Detector on the Other Side of Ordnance

There are three types of nuclear technology employed for explosive detection: electron-beam X-ray activation, thermal neutron analysis, and neutron thermalization gauge. The biggest difference between the first and the next two is the source of the radiation; thermal neutron analysis and neutron thermalization gauge excites the element in an explosive by generating neutrons from radioisotopes such as Californium-252, rather than using X-rays.

Soil and encased explosives have high X-ray attenuation rates, making that technique non-ideal for buried OEW detection. However, thermal neutron analysis has successfully been employed for the detection of metallic and non-metallic land mines.

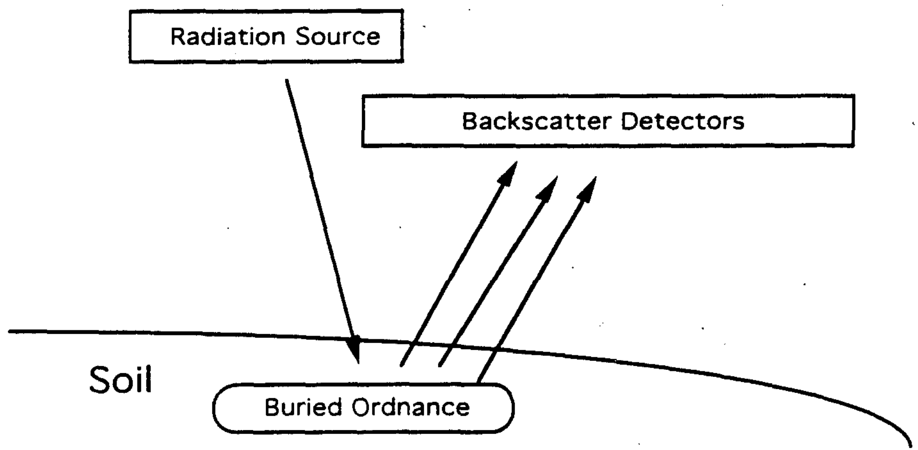

Figure 2.3.8.2 The Use of Backscatter Detector to Detect Ordnance.

2.3.8.1. Electron-Beam X-Ray Activation

In electron-beam x-ray activation, the area is illuminated with an intense x-ray source. When the nitrogen in the explosive is excited by the x-rays, gamma rays are emitted as a by-product. The gamma rays produced by the nitrogen have a characteristic half-life of approximately ten minutes with an intensity of 0.511 MeV (10^6 electron volts is a convenient unit for measuring energy in nuclear physics). In contrast, other common elements typically have much shorter or much longer half-lives. These facts can be exploited in detecting the nitrogen. The gamma ray detector can be activated during the expected 10 minute half-life period, and tuned to search for gamma rays in the 0.511 MeV region. Using this technique results in a high signal-to-noise ratio and is shown in Figure 2.3.8.3.

OEW detection using this method has several drawbacks. The radiation generator is usually quite bulky (normally weighing about 3500 lb.); thus, the generator requires a truck to carry. It also produces levels of radiation that are unsafe for humans, thus requiring remote operation. Figure 2.3.8.4 shows a portable radiation generator mounted on a remotely controlled vehicle which is used to illuminate an area 15 ft. in front of from the detectors. The detectors which are mounted 20 ft. in front of the truck (on the front bumper of the vehicle) detect the unique signatures of the mine and determine its location. When a piece of OEW is detected, the heavy vehicle stops, and a clean-up crew is sent out to dig into the soil and dispose of the OEW. As soon as the OEW is safely disposed of, the vehicle continues to look for the ordnance in the same fashion as discussed above.

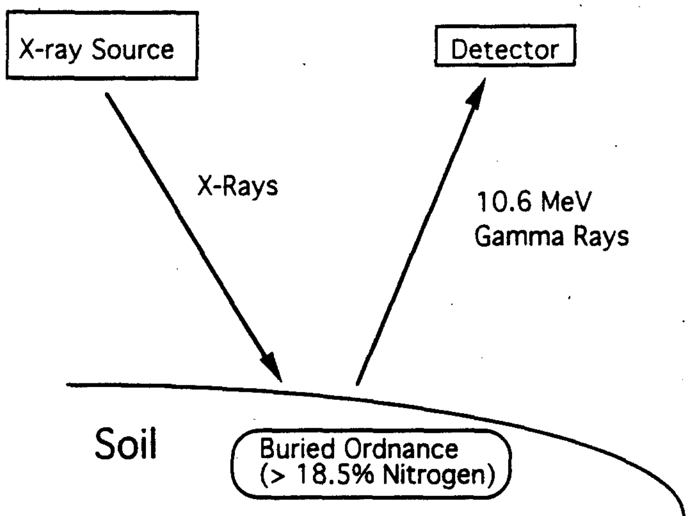

Figure 2.3.8.3 Explosive Detection via Electron-beam X-ray Activation

In addition, radiation is significantly attenuated by the soil, so nuclear technology can only be used to detect explosives that are less than two feet deep. Moreover, these schemes do not work well with explosives in metal casings since the radiation is also attenuated by metals. Therefore, x-ray activation technology is most useful when detecting mines or plastic explosives which are usually located at shallow depths. Improvements to this technology in the future may come from advances in source and detector technologies.

The above concept is known as MIne Detection with Energetic Photons (MIDEP). It has subsequently been renamed as Explosive Detection with Energetic Photons (EXDEP). EXDEP was field tested in 1992. In experimental tests, this system's detection thresholds allowed it to detect several test OEW pieces: a 9.5 kg mine buried to a depth of 10 cm, a 1.5 kg mine buried to a depth of 5 cm, and a 0.2 kg mine on the surface. Detection was found to be robust, even when the soil was rich in organic materials which usually contains nitrogen and phosphorus. Speeds of 1 mile per hour were used in the field tests. Calculations show that the technique can have quite good detection probabilities (> 99%) and very favorable false alarm probabilities (< 1%).

This method will probably not work for explosives in thick metal casings because of the casings' relatively high attenuation of the 0.511 MeV radiation. The tests were unsuccessful for explosives buried deeper than 10 cm. Furthermore, remote operation is required because of the high radiation levels used. Thus, it seems that the use of the MIDEP/EXDEP concept for buried OEW detection is limited.

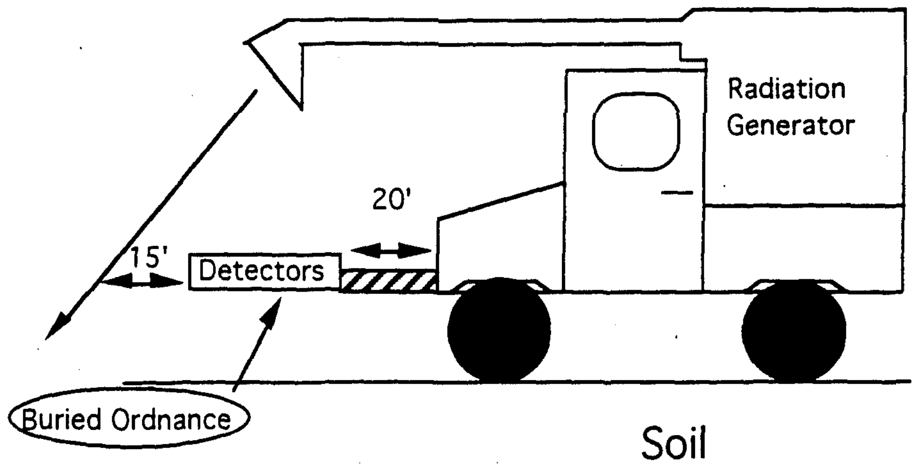

Figure 2.3.8.4 A Portable Radiation Generator Mounted on a Remotely-Controlled Vehicle

2.3.8.2. Thermal Neutron Analysis

Thermal neutron analysis (TNA) is the best known nuclear technique and was funded for several years by the Federal Aviation Administration (FAA) for the detection of explosives at airports. The differences between TNA and electron-beam x-ray activation is both the radiation source used and the observed radiation. TNA excites the nitrogen in the explosive by thermal neutrons. A "bath" of neutrons are generated by a Californium-252 source and then moderated; they then penetrate the examined object. The radiated nitrogen is then excited and produces gamma rays of very high energy (approximately 10.8 MeV) that are unique to nitrogen. The density of nitrogen in an object may then be deduced by the gamma ray intensity.

Of interest is that this same nuclear technique may be utilized to obtain density of hydrogen in an object. In this manner, data obtained while looking at the nitrogen signature may be correlated with data from the hydrogen signature for a lower false alarm rate. Information on location of these concentrations within the object is available: good transverse resolution (within approx. 3 inches) is obtained, but the depth resolution is not good. Additionally, when maintaining a fast speed of advance, experience has shown that in order to be sensitive to the small quantities of explosives that must be found, one must reduce TNA device detection thresholds to the point that they suffer from a high false alarm rate. Although not perfect, the determination of nitrogen or hydrogen content is a useful tool for distinguishing explosives from many common items.

Many systems have been installed in international airports worldwide. Actual experimental values for detection as a function of explosive mass are classified by the Department of Transportation; however, it was found that detection rates of nearly 100% can be achieved. Because the FAA requires a rate of 10 bags per minute, significant false alarm rates (18% to 20%) are experienced. If these throughput requirements are relaxed, much better performance values can be expected.

As with electron-beam x-ray activation, this technology for ordnance detection indicates that it may be effective in mine detection, but probably will not be an effective method of detecting deeply buried (over 2 feet) ordnance. Thermal neutrons cannot penetrate soil well, and some soils that have been treated with artificial fertilizers have high concentrations of ammonia (nitrogen and hydrogen), which may result in high false-alarm rates.

One advantage of this type of sensor is that the detection process is not affected significantly by the container of the OEW (metal, plastic or glass). In addition, this technique senses chlorine, a constituent of mustard agents. This results in the ability to differentiate between chlorine-laden chemical weaponry and conventional UXO.

2.3.8.3. Neutron Thermalization Gauge (NTG)

The neutron thermalization gauge is technically a type of Thermal Neutron Analysis (TNA, see Section 2.3.8.2), but has evolved into its own independent category. Like TNA, NTG also detects explosives by identification of hydrogen's unique backscatter signature when irradiated with thermal neutrons. NTG systems are small enough and light enough to be considered portable.

The practical differences between TNA and NTG is that TNA is very specific in its output; it can show locations and give a positive ID on its findings, at the expense of a relatively slow processing time. NTG, in contrast, is non-specific and hence is relatively fast; it is ideal for a first-pass site survey. Both types are best used in conjunction with other sensors, such as magnetometers and GPRs, to decrease the false alarm rate and enhance the object identification.

2.3.9. Acoustics

The ability to "see" with sound has long been an intriguing concept. True-focused, orthographic images in real-time of objects illuminated with sound rather than light are possible. Acoustics have been used for the detection of distant objects on the ground and under water. The Waterways Experimental Station (WES) has employed acoustic technology to locate OEW at Lake Erie.

Moreover, the Naval Surface Warfare Center (NSWC) - Coastal Systems Station (CSS) has used sound to detect sea mines.

The human ear is sensitive to frequencies between about 20 Hertz (Hz) and 20,000 Hz as shown in Figure 2.3.9.1. Frequencies lower than 20 Hz are called seismic or infrasonic; those higher than 20,000 Hz are called ultrasonic. Seismic waves are usually used for land-based applications; whereas ultrasonic waves are used for airborne and underwater applications. With regard to terminology, the terms "acoustic," "sound," "sonar," and "sonic" are considered to be unrestricted in frequency range.

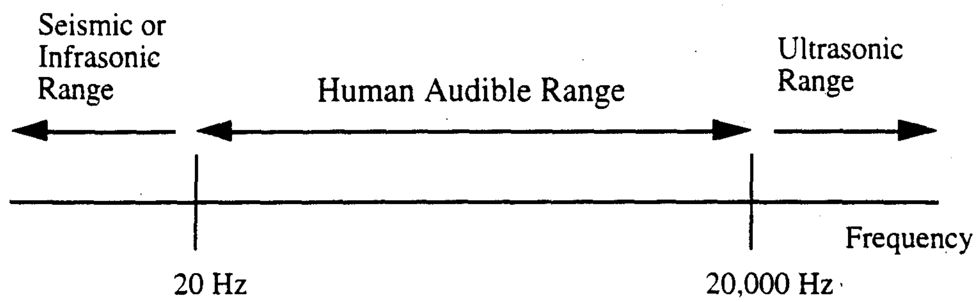

Figure 2.3.9.1. Acoustic Frequency Range

2.3.9.1. Seismic or Infrasonic Waves for Land-Based Applications

The seismic technique is used for land-based applications and can be best illustrated by the operation of a cone penetrometer which is being used to solve geological engineering problems today. The penetration of the probe of a cone penetrometer creates seismic ground waves (like earthquakes). As soon as the waves hit an object in the soil, the waves are echoed or bounced back at a much higher rate than soil which contains no buried objects. The seismic or motion sensor located on the probe conducts seismic shear and compression wave surveys. These surveys may locate the buried object in the soil by examining the seismic/sound waves. Thus, this type of seismic survey may be used to locate buried OEW by the observation of the reflected waves. However, the successful application of the reflection seismic techniques is very difficult due to the irregularity in the compactness of a soil.

2.3.9.2. Ultrasonic Waves for Airborne and Underwater Applications

The ultrasonic acoustic technique or ultrasound can be used for airborne and underwater applications. One commonly used device, called an ultrasonic transducer, converts electric energy into ultrasonic waves. Some ultrasonic transducers include a special disk made of quartz or of a ceramic material. When charged with electricity, the disk vibrates so rapidly that ultrasonic waves are created.

Many transducers can also convert ultrasonic waves into electrical energy. These transducers give off ultrasonic waves at the same time that they change the returning echoes back to electricity. Strong echoes create stronger electric pulses than weak ones do. A computer registers such data as the intensity of the electric pulses and the direction of the returning echoes. The computer can then provide information on the substances that reflected the ultrasonic waves. Some of these computers transform the data they receive into images on a screen.

2.3.9.2.1. Ultrasonic Waves for Applications in Air

In the early 1970s, a hand-held sonar blind guidance device showed promise for the application of ultrasonic waves in air. In this device an ultrasonic beam is radiated; the presence of an obstacle causes this beam to be reflected, and the reflected beam is indicated by a tone in a headset worn by the operator or the blind in this case. The pitch of the tone indicates the distance to the obstacle.

In principle, ultrasonic waves can be applied to airborne surveillance systems to detect OEW in a similar fashion as the hand-held sonar blind guidance device. A transducer located on an airplane or helicopter will generate ultrasonic acoustic frequency which propagates through the air. These acoustic signals will bounce off the ground; and the return of these waves can map the ordnance. It is capable of penetrating the ground to a certain level. Based on the return of the waves, the ordnance is mapped as an odd-shaped object using imaging processes. Note: An imaging system is definitely required in this scheme. Moreover, using this acoustic technique to detect buried ordnance may not be possible because the sound waves are refracted when the sound crosses a different boundary (e.g. in going from air to Earth or vice versa) due to the non uniformity of the densities of the two mediums. Thus, "robust" ordnance detection may not be possible.

2.3.9.2.2. Ultrasonic Waves for Applications Under Water

Ultrasound has become a very effective method for the detection of underwater objects such as submarines. This scheme employs a beam of sound pulses which sweeps the water horizontally; when it strikes a solid object, an echo is returned, providing a bearing on the object. The distance may be found from the knowledge of the sound velocity in water which is 1498 m/sec at 20° C. This scheme can be used to detect and locate OEW. However, there are limitations involved. It usually employs rather large transducers. The use of sonar demands many correction techniques to take care of temperature gradients, changes in density, reflection from surface and bottom of the sea, and other error-producing effects. However, a synthetic aperture sonar technique, whose principle of operation is very similar to SAR, has been developed to overcome the resolution limitation caused by the small transducer.

2.3.9.3. Acoustic Imaging

Imaging techniques will improve the detection and location of OEW. By now, a wide variety of system concepts for acoustic imaging exist for airborne, land-based, and underwater applications. Some of the newer systems, which will be discussed in detail below, range from the purely holographic to the purely lens types for underwater applications.

2.3.9.3.1. Holographic Imaging

A hologram is a three-dimensional picture made on photographic film (without use of a camera) by the pattern of interference formed by laser light reflected from the object; the picture is viewed by passing laser light through the film. In recent years, optical holography has appeared as a powerful tool for optical imaging. Some work is being carried out to develop an ultrasonic hologram. In one system, illustrated in Figure 2.3.9.2, two beams of ultrasonic waves at identical frequencies are directed at an angle to the underside of a liquid surface. One of these beams passes through the object to be investigated. At the surface, the two beams interfere to produce an ultrasonic wave pattern containing, effectively, an ultrasonic hologram of the object. This wave pattern is visualized by shining single-frequency light at an oblique angle onto the liquid surface. The liquid wave pattern behaves like a diffraction grating and the first order diffraction image contains a picture of the ultrasonic cross section. In fact, the light beam is behaving in the same way as the beam used to reconstruct a picture from an optical hologram. Ultrasonic holography, as so far developed, may be able to improve the detection and location of underwater objects or OEW.

2.3.9.3.2. Acoustic Lens Imaging

For physics-based reasons, most imaging of underwater objects relies on acoustic and optical sensors. Cameras and other optical systems have far higher resolution than sonars, but they also have several drawbacks. Since water is approximately a thousand times denser than air, it rapidly absorbs optical energy. Thus, optical sensors are limited to ranges of tens of meters under the best conditions. Also, optical systems fail at centimeter ranges in highly turbid water, a condition common in coastal waters or water disturbed by people.

A different approach to acoustic sensor development is the acoustic lens, a sonar analogous to the human eye. An acoustic lens consists of a thin hemispherical shell and a retina filled with transducers (see Figure 2.3.9.3). The cavity between the retina and the shell is filled with a specially chosen fluid that focuses incoming

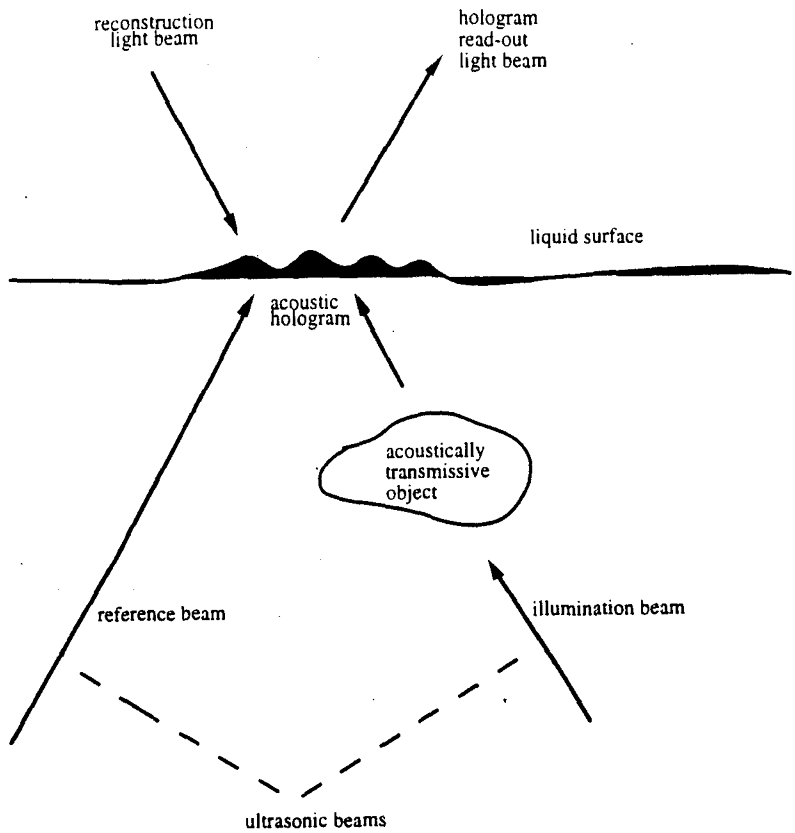

Figure 2.3.9.2. System for Production of Ultrasonic Hologram

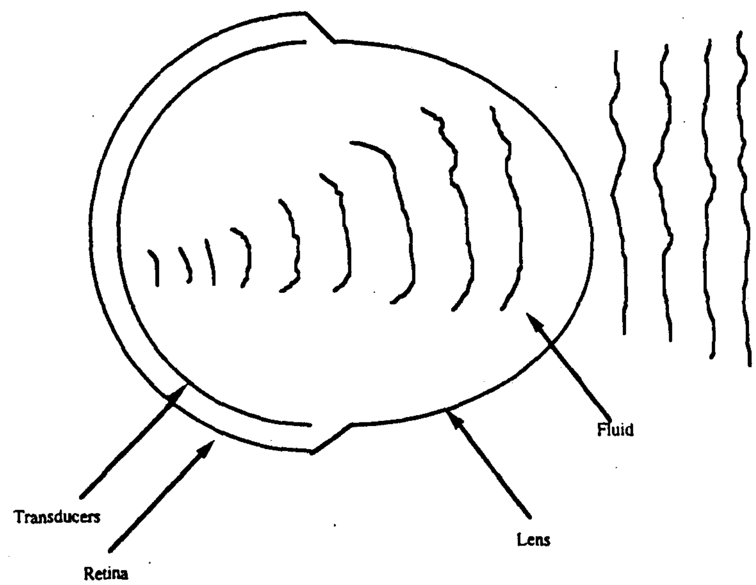

Figure 2.3.9.3. Acoustic Lens

acoustic waves on the retina. Sound coming from a single direction is focused on a single transducer. The lens both transmits and receives acoustic signals. When back scatter from a transmitted acoustic signal is received at the lens, the position on the retina of the receiving transducer yields bearing and elevation coordinates. The time delay between transmission and reception determines the range of the object in question.

2.3.9.3.3. Problems with Underwater Imaging

Several problems make underwater imaging difficult:

(1) Insufficient data due to the current sonar transducer design introduce limitations. The state-of-the-art design for sonars only has one-degree beams; thus, the data samples are an order of magnitude too crude, in both elevation and azimuth (i.e. the horizontal angular distance from a fixed reference direction to an object) to produce detailed images. To alleviate this technical constraint, a computational-intensive sonar beam-forming technique could be applied to produce a sharply focused acoustic beam.

(2) Uncertain position information is a disadvantage in acoustic imaging. Precise navigational positioning in the ocean is rarely achieved. Ocean bottom mapping missions find that intersecting perpendicular swaths of ocean bottom measurements typically misregister by hundreds of meters.

(3) An often noisy environment is present. Acoustic returns at the sonar are not reflections--they are back scattering from objects within the path of the acoustic transmission, including the ocean bottom. This creates a noisy environment in which imaging both artificial and natural objects is a challenging undertaking.

2.3.9.4. Common Disadvantages of the Seismic and Ultrasonic Acoustic Technology

The immediate application of existing sophisticated acoustic techniques to ordnance detection does not seem possible due to the following reasons:

(1) The ability to discriminate between ordnance and natural objects like rocks may not be possible because both produce strong reflections of acoustic signals. Thus, the acoustic sensor will detect a large number of false alarms.

(2) Acoustic techniques usually require the employment of a rather large device to generate the acoustic waves.

(3) These acoustic schemes encounter difficulties when a sudden discontinuity in the material density occurs such as irregular and unpredictable nature of soil (e.g. different degrees of soil compaction) in land-based applications or variations in temperature in airborne and underwater applications. This sudden discontinuity in material density makes it difficult to interpret the results using acoustical means.

2.3.9.5. Summary of Acoustic Imaging

The fundamental limitation in acoustic imaging today is low sensor resolution rather than inadequate visualization algorithms. New technologies will replace the piezoelectric ceramic materials that make up the elements on the lens retina with smaller, more sensitive retinal elements. High-resolution imaging to faithfully reproduce an object of interest will then be possible. But even using today's sensor technology, we can combine visualization and imaging algorithms to produce acoustic "snapshots" that correctly estimate an object's size, reasonably approximate its shape, and show some of its fine-scale details.

Acoustic technology may not be suitable for airborne and land-based applications. However, sound is currently considered to be a viable technique for the detection and location of OEW for underwater applications.

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2.4. SUMMARY OF SENSOR TECHNOLOGIES

This section summarizes the characteristics associated with each of the sensors described in Sections 2.2 and 2.3 and provides the information in tabular form. The first table describes the use of each sensor class as it applies to terrain or the sensing of an object. Where there are several different types of sensors within a sensor class (for example, there are seven different kinds of magnetometers), subsequent tables highlight their performance differences. (As a further aid in sensor selection, Section 3 takes into account terrain types and recommends sensors to use for the most pressing RAC 1 base sites. Refer to Section 3 for additional guidance.)

2.4.1. Selection Chart - Sensor Type vs. Capabilities

Table 2.4.1.1 summarizes the basic detection capabilities for each class of sensor technology that could be used for unexploded ordnance (UXO) detection. In this table, the rating "shallow" was considered to be "a few feet" deep in soil, and the rating "deep" was considered to be "from a few feet to several yards" in depth. Actual penetration depths will vary in range depending on the sensor, the soil, environmental conditions, and the object being sensed.

Table 2.4.1. Sensor Type vs. Capabilities

Sensor type	Detection Capabilities								
	Ferrous metal	Non-ferrous metal	Other Man-Made Objects	Depth	Imaging Capability	Land	Air-borne	Under-water	Plat-form
Magnetometer	yes	no	no	shallow	no	yes	yes	yes	air, ground, handheld
EM	yes	yes	no	shallow	no	yes	yes	no	air, ground, handheld
Ground Penetrating Radar	yes	yes	yes	deep	yes	yes	yes	yes (fresh water)	air, ground
Acoustic (imaging)	yes	yes	yes	shallow	yes	yes	pos-sible*	yes	air, ground
Infrared	yes	yes	yes	shallow	yes	yes	yes	no	air
MMW	yes	yes	yes	(surface only)	yes	yes	yes	no	air
Visible Imaging	yes	yes	yes	(surface only)	yes	yes	yes	yes	air, ground
LIDAR	yes	yes	yes	(surface only)	yes	yes	yes	yes	air, ground
Nuclear Technology	no	no	yes	shallow	yes	yes	no	no	ground
Interferometric Impulse Radar	yes	yes	yes	deep	yes	yes	yes	no	air, ground

* The speed of sound may be too slow for airborne applications.

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2.4.2. Magnetometers/Gradiometers Characteristics

Table 2.4.2 contains a summary of the performance parameters associated with the seven types of magnetometers described in Sections 2.2.1 and 2.3.1

Table 2.4.2 Magnetometers/Gradiometers Characteristics

Sensor Types	**Sensitivity**	**Field Vector Detection**	**Electro-magnetic noise immunity**	**Maturity**	**Mobility**
Proton Precession Magnetometer	0.1 gamma	possible	poor	yes	portable
Optically Pumped Magnetometer	0.05 gamma	possible	good	yes	transportable
Fluxgate Magnetometer	0.1 gamma	yes	poor	yes	portable
Fiber-optic Magnetometer	1.0 gamma	yes	extremely good	products starting to appear	portable
SQUID Magnetometer	0.001 gamma	yes	good	products starting to appear	transportable

2.4.3. Electromagnetic Induction Sensors Characteristics

Table 2.4.3 provides a summary of the characteristics of airborne and ground-towed electromagnetic (EM) induction sensors as described in Section 2.2.2 and 2.3.2

Table 2.4.3 Electromagnetic Induction Sensors Characteristics

EM Sensor Type	**Along-track**	**Resolution Cross-track**	**Resoluti on Vertical**	**Penetration Depth**
Ground-Towed Induction system (Pulsed)	2m	2m	none	< 2m
Helicopter-borne EM system (Low Frequency Continuous Wave)	100m	100m	none	< 25m

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2.4.4. Ground-Penetrating Radar Characteristics

Table 2.4.4 provides a summary of the performance parameters associated with the three types of ground-penetrating radar described in Sections 2.2.3 and 2.3.3

Table 2.4.4 Ground-Penetrating Radar Characteristics

GPR Type	Along-track	Resolution Cross-track	Vertical	Penetration Depth
Ground-Towed	1m	1m	1m	Ice, frozen soil, dry sand: 20m max. Clay: 1m max.*
Airborne Vertical Profiler	1m	30m	1m	Ice, frozen soil, dry sand: 20m max. Clay: 1m max.
Synthetic-aperture Radar	1m	1m	1m	1m

2.4.5. Acoustic Characteristics

Table 2.4.5 provides a summary of the performance parameters associated with the three types of acoustic technology described in Section 2.3.9.

Table 2.4.5 Acoustic Characteristics

Sensor Types	Detection Capability	Noise Immunity	Maturity	Mobility
Transient	N/A	N/A	N/A	N/A
Seismic	Objects 3 m away from the seismic wave generator	poor	emerging for the application of detecting and locating OEW	bulky
Ultrasonic	Objects less than 1m away from the transducer	poor	emerging for the application of detecting and locating OEW	bulky
Acoustic Imaging	Objects less than 1m away from the device	poor		bulky

* These are typical values. The US Geological Survey has reported penetration depths of up to 5300 m in polar ice.

2.4.6. Visible Imaging (CCD) Characteristics

Table 2.4.6 provides a summary of typical performance parameters associated with the charge coupled devices (CCDs) of visual imagers described in Sections 2.2.4 and 2.3.4.

Table 2.4.6 Typical Performance Parameters of CCDs

Pixel Count	Pixel Size	Dynamic Range	Data Conversion	Processing Rate
4096 x 4096	7.5 micron	> 800	14 bit	50 kpixel/sec
1024 x 1024	9 micron	> 450	8 bit	1 megapixel/sec
800 x 800	7.5 micron	> 500	12 bit	100 kpixel/sec

2.4.7. Infrared Characteristics

Tables 2.4.7 (a and b) provide a summary of the performance parameters associated with the types of infrared radiometers and spectrometers described in Sections 2.2.5 and 2.3.5.

Table 2.4.7.a Infrared Radiometer Characteristics

Type	Waveband	Spatial Res. (m)	Min. D Temp. (K)
Handheld/backpack	MWIR	0.1	0.01
Handheld/backpack	TIR	0.1	0.01
Vehicle mounted	MWIR	1	0.05
Vehicle mounted	TIR	1	0.05
Airborne	MWIR	50	0.1
Airborne	TIR	50	0.1

Table 2.4.7.b Infrared Spectrometer Characteristics

Type	Waveband	Spatial Res. (m)	Spectral Res. (nm)
Handheld/backpack	MWIR	0.02	10
Handheld/backpack	TIR	0.05	10
Vehicle mounted	MWIR	0.2	10
Vehicle mounted	TIR	0.5	10
Airborne	MWIR	30	10
Airborne	TIR	50	10

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2.4.8. MMW Characteristics

Table 2.4.8 provides a summary of the performance parameters associated with the types of millimeter wave radiometers described in Section 2.3.6.

Table 2.4.8 MMW Radiometer Characteristics

Type	Antenna diameter (m)	Min. Δ Temp. (K)	Resolution (milliradian)
35 GHz	1.0	0.3	3
94 GHz	1.4	0.1	1

2.4.9. LIDAR Characteristics

Table 2.4.9 provides a summary of the performance parameters associated with LIDAR types described in sections 2.2.6. and 2.3.7.

Table 2.4.9 LIDAR Characteristics

Type	Applications	Wavelength
2-D Imaging LIDAR	Surface/underwater OEW detection	Visible/IR
3-D LIDAR	Surface/air chemical trace detection	UV/IR

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2.4.10. Nuclear Technology Characteristics

Table 2.4.10 is a summary of the performance parameters associated with the three types of nuclear technology described in section 2.3.8.

Table 2.4.10 Nuclear Technology Characteristics

Sensor Types	Detection Threshold	Noise Immunity	Maturity	Mobility
Electron-beam X-ray Activation	>9.5 kg mine buried at 10 cm, >1.5 kg mine buried at 5 cm, and >.2 kg of mine on the surface	good for surface detection limited for buried OEW	field testing stage	not portable due to shielding; the weight of the radiation generator which is 3500 lb.
Thermal Neutron Activation	tested	good for surface detection, poor for buried OEW	emerging for the application of detecting and locating OEW	portable
Neutron Thermalization Gauge	data unavailable as of this printing	good for surface detection, poor for buried OEW	emerging for the application of detecting and locating OEW	portable

2.4.11. Comparison of Sensor Technologies' Response to Common Forms of OEW

A chart showing the relative sensitivity of the GPR, Magnetometer, and Electromagnetic sensors to various metallic ordnance, other man-made targets, and rocks is provided in Table 2.4.11. This data is based upon a thorough understanding of the theoretical limits and strengths of differing sensor technologies, and is not necessarily indicative of the quality of a vendor's implementation. A definition of the ranking symbols appears below:

● **Most Applicable** - under the given conditions, these technologies will provide the best performance in their respective areas.

◒ **Average** - this technology will work adequately under the stated conditions, although there are other technologies reviewed herein that will perform the job faster, with greater sensitivity, from greater distances, or with fewer false alarms.

○ **Poor** - under the stated conditions, this technology is not recommended to be used for the detection and location of OEW.

These ranking symbols represent a combination of relative values and absolute ratings. When two sensor types are ranked differently, it can be interpreted to

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mean that the higher-ranked sensor will perform better on the indicated ordnance type than will the lower-ranked sensor. If no sensor will adequately locate an ordnance type, none are ranked highly.

Table 2.4.11 Comparison of Sensor Technologies' Response to Common Forms of OEW

Sensor Type	Large (155 mm) Shells	Small (20mm) Shells	Non-Ferrous Ordnance - Large	Non-Ferrous Ordnance - Small	Rock	Wood	Tire	Chemical explosives	Footnotes
GPR - Land	●	◕	●	◕	●	◕	●	○	1
GPR - Air	◕	◒	◕	◒	◕	◒	◕	○	2
EM - Land	●	◕	●	◕	○	○	○	○	
EM - Air	◕	◒	◕	◒	○	○	○	○	
Magnetometer - Land	●	◕	○	○	○	○	○	○	
Magnetometer - Air	◒	◔	○	○	○	○	○	○	
IR Radiometry - Land	◕	◒	◒	◔	◒	○	○	○	3
IR Radiometry - Air	◕	◒	◒	◔	◒	○	○	○	3
IR Spectrometry - Land	●	◕	◕	◒	◕	○	◔	◒	
IR Spectrometry - Air	◕	◒	◒	◔	◒	○	○	◔	
Acoustic - Land	◒	◔	◒	◔	◒	◒	◒	○	
Acoustic - Air	○	○	○	○	○	○	○	○	
LIDAR - Land	●	◕	●	◕	◕	◕	●	●	4
LIDAR - Air	●	◒	●	◒	○	◒	●	◕	4
Nuclear Techniques - Land	○	○	○	○	○	○	○	●	
Nuclear Techniques -Air	○	○	○	○	○	○	○	○	
Visible Imaging - Land (surface)	●	●	●	●	●	●	●	○	5
Visible Imaging - Air (Surface)	●	●	●	●	●	●	●	○	5
MMW Radiometry - Land	◒	◔	◔	○	◔	○	○	○	6
MMW Radiometry - Air	◒	◔	◔	○	◔	○	○	○	6

Scale: ○ ◔ ◒ ◕ ●

Poor Average Most Applicable

1 Cannot easily differentiate between OEW and other clutter
2 Airborne covers larger area per day, but with lower resolution.
3 Applies to surface OEW only.
4 Applies to unobscured surface OEW only.
5 Applies to unobscured surface OEW only on clear days.
6 Can see through precipitation

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Section 3

SENSOR TECHNOLOGY ASSESSMENT

The sheer diversity of terrain conditions and the ideal conditions conducive to each sensor type make it difficult to properly match a sensor to the terrain to be surveyed. Given the strengths and weaknesses of the technologies and sensors described in the Tutorials (Section 2) and Sensor Products (Section 4), this section strives to assess the sensor technology and demonstrate the sensor selection process for the environmental constraints dictated by a selection of the most urgent RAC 1 (Risk Assessment Code - Priority 1) sites.

3.1. OVERVIEW

With the recent closure of a host of military bases and subsequent pressures to transfer these facilities to civilian users, an urgency has developed to locate and rid these regions of toxic and hazardous materials. Of the greater than 900 formerly used defense sites being examined for hazardous conditions, including the threat of buried unexploded ordnance, barely a third of the site characteristic studies (or archive studies) of these sites have been completed to date. Of the remaining sites, approximately 300 have resulted in RAC 1 classifications, the highest priority for remediation.

The Risk Assessment Code (RAC) is a prioritization scheme used to classify sites in need of remediation. The definitions are as follows:

RAC 1	Imminent Hazard - Emergency action required to mitigate the hazard or protect personnel (i.e., fencing, physical barrier, guards, etc.).
RAC 2	Action required to mitigate hazard or protect personnel. Feasibility study is appropriate.
RAC 3	Action required to evaluate potential threat to personnel. High priority confirmation study is appropriate.
RAC 4	Action required to evaluate potential threat to personnel. Confirmation study is appropriate.
RAC 5	No action required.

With the exception of the Yuma Proving Grounds, the recommendations given in this section only deal with those sites that have received a RAC 1 rating by the Corps of Engineers. The Yuma Proving Grounds, located at Yuma, AZ, will also be experiencing ongoing cleanup and remediation of ordnance and explosive waste (OEW). Although not a RAC 1 site, the clean-up operations are as equally hazardous to personnel as any expected for RAC 1.

Of the 300 potential sites, 30 were selected to illustrate the rational for sensor selection to be utilized in the characterization of specific sites. Although no

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single sensor is appropriate for appropriate for the evaluation of all sites, the methodology presented herein is applicable to all sites and can be used to select the appropriate sensor (or sensor suite) for site characterization.

The location of buried ordnance represents the most severe challenge of the remediation task, and it is toward this objective that this technology assessment specifically focuses. The recommended approach for the assessment and selection of the appropriate sensors to accomplish the task of detecting and locating buried ordnance is first to identify the sites' geographic locations, after which the geological and environmental conditions at each site, such as soil type and vegetation, can be determined. These steps would then be followed by the superposition of sensor capabilities onto the constraints imposed by the site conditions, resulting in an estimated effectiveness of a selection of sensors which could be applied to that specific site.

Given the geographic location of a site, the site geology and vegetation can, at least to a first order, be independently determined with sufficient accuracy to evaluate sensor effectiveness for sensors applied to that site. A myriad of charts depicting soil conditions, vegetation, and terrain are available from such sources as the U.S. Geological Survey and the U.S. Department of Agriculture, and such sources were indeed used for this assessment. However, one would expect that the superposition of all available sensors onto the conditions existing at the various sites would result in a case such as that depicted conceptually in Figure 3.1.1. While the majority of cases may be adequately represented, there will be some sensors which will not be applicable to any site, and more importantly, there will undoubtedly be some sites, or areas within specific sites, where the conditions will be such that none of the available sensors will be very effective. These sites, although expected to be in the minority, must be treated on a case-by-case basis.

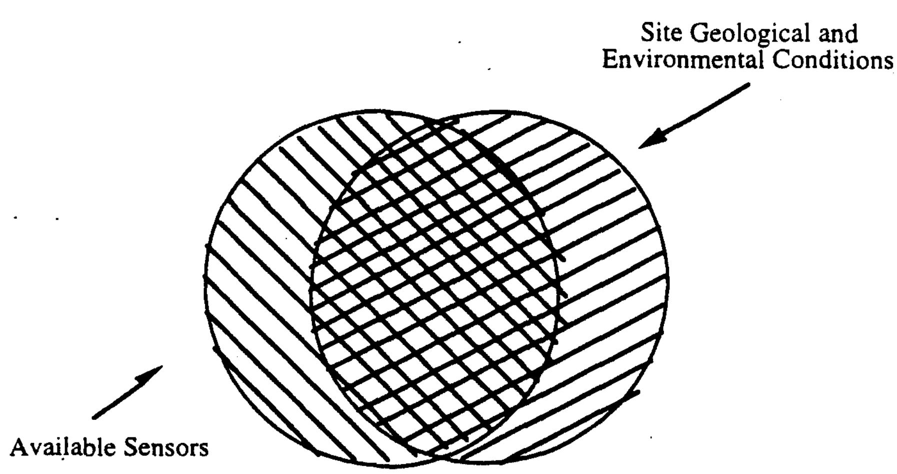

Figure 3.1.1. Overlay of Sensors with Site Conditions

3.2. IDENTIFIED SITES

3.2.1. Geographic Locations of Sites

The site locations representing 31 of those most urgently in need of clean-up were provided by the U.S. Army Corps of Engineers. These are presented in Table 3.2.1 below and are depicted on the map, Figure 3.2.1.1.

Table 3.2.1. Partial List of the Most Urgent RAC 1 Sites

Map Location†	State	Site	Nearest Town
1	AL	Camp Siebert Gun Range	Attalla
2	CA	Camp San Luis Obispo	San Luis Obispo
3	CA	Camp Elliot Air Field	San Diego
4	CA	CPSLO-Ernest Vollmer, Jr.	San Luis Obispo
5	CA	Santa Rosa AAF Station	Santa Rosa
6	DC	Spring Valley Air Field	Washington
7	GA	Mustard Gas Burial Site	Manchester
8	GN	War in Pacific-Guamsea	Asannisdeo
9	IN	Camp Atterbury (Ammo Plant)	Edinburgh
10	IL	Camp Grant Rifle	Rockford
11	HI	Heeia Combat Training Camp	Heeia
12	MA	Camp Wellfleet Field	Chatham
13	MA	Butler Point Battery Burial Site	Marion
14		:[Site deleted from list]	
15	MD	Johns Hopkins University	Baltimore
16	MI	Camp Clayban AAA Firing Range	New Era
17	MI	Ft. Custer Rec Red Arkapo	Augusta
18	MO	Tyson Valley Powder Farm	Eureka
19	MS	Gulfport Army Air Field	Gulfport
20	MS	Camp Shelby Maneuver Area	Hattiesburg
21	NC	Camp MacKallin	Hoffman
22	NC	Charlotte Naval Ammunition Depot	Charlotte
23	NC	Laurinburg-Maxton ABO Fac	Laurinburg
24	NE	Sioux Army Depotage Houma	Sidney
25	NE	McCook Army AF Station	McCook
26	NJ	Ft. Hancock Rifle Range	Highlands
27	NY	Sampson Air Field	Willard
28	SC	Camp Croft Powder Farm	Spartanburg
29	SC	Lake Murray Bombing Range	Lake Murray
30	TX	Dalhart AAFCHY Amphibian Base	Dalhart
31	VA	Buckroe Beach Station #27	Buckroe Beach
32	VI	Former Fort Segarra Island	Charlotte Amalie

† Location identifier for Figure 3.2.1.1.

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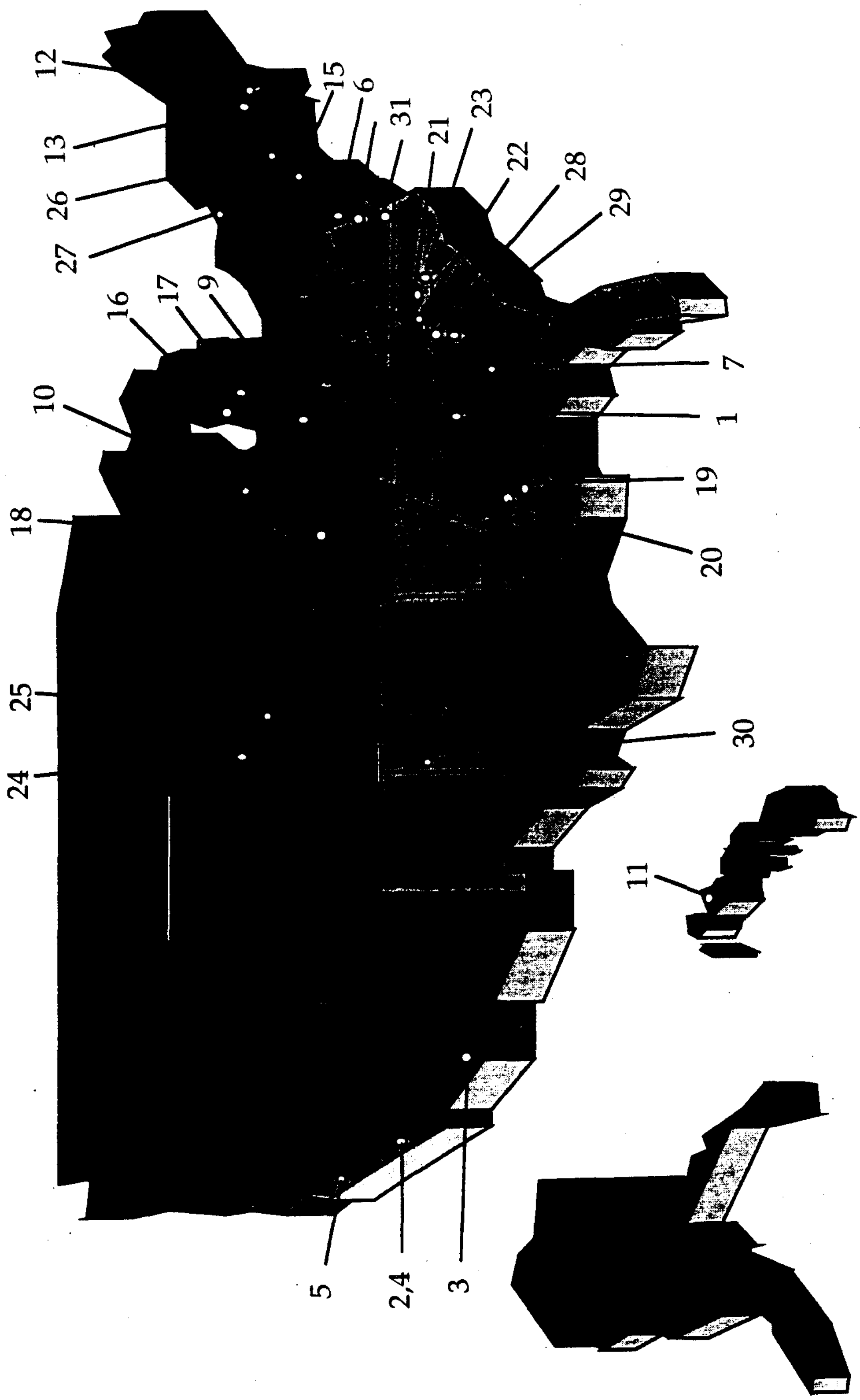

Figure 3.2.1.1. Partial List of RAC 1 Site Locations

3.2.2. Scope of the Detection and Location Task

The vast diversity of ordnance and explosive waste, coupled by the very nature of its designed use in training exercises (e.g., artillery firing, bombing practice), renders the detection and location of OEW a very difficult task. In concentrated target areas such as firing ranges, the task scope is less formidable as the approximate perimeter is relatively well defined. However, in regions of live fire exercises designed to expose personnel to the experience of live rounds, the impact regions are more diffuse. A falling artillery round does not always detonate, and it can penetrate the ground by as much as two to three meters, a typical depth for buried OEW. Other OEW concentrations are burial sites where obsolete munitions are intentionally disposed of. For example, it was not uncommon in the past for unused munitions nearing expiration of their useful life to be buried in close proximity of the firing range. The disposal of chemical waste by burial is another example. The mustard gas burial site in Manchester, GA, and the Butler Point battery burial site near Marion, MA, are typical cases.

A site that has not been used for some time is subject to vegetation overgrowth, especially in the warmer, wetter climates. The obvious impact on sensor selection is to make the initial detection more difficult by obscuring evidence of ground disturbance. The influence of the regional geology is a distinctively important factor. Not only will the differences in soil density affect a munition's penetration depth, but the different soil groups will also affect the sensors.

Soil with high clay content and/or a high salinity water table will impede the performance of ground penetrating radar. Soils of high volcanic content, dark igneous rocks, or large concentrations of iron will impact the performance of magnetometers. The effect of the local climate on the geology can be quite dramatic. Impact scars can remain obvious for years in a dry climate, whereas they are readily and quickly obscured where it is wet.

All of the above factors are further exacerbated by the recent base closures and the resulting urgencies to transfer ownership to the civilian sector. To make matters worse, many of the RAC 1 sites are already in urban areas or are surrounded by population centers. This is the case, for example, with Camp Elliot Air Field in San Diego and Johns Hopkins University in Baltimore.

3.3. SITE GEOLOGICAL AND ENVIRONMENTAL CONDITIONS

The most dominant influence directing the intelligent selection of a set of sensors for the detection and location of buried ordnance are the site geological and environmental conditions. Geological conditions for the purpose of this report will comprise the site soil geology, terrain conditions, and soil conductance or dielectric constant. Both parameters are interchangeable through a simple relationship. The vegetation will be that indicative of the most prevalent local indigenous species. The vegetation identified is that which would reasonably be expected to be found within the site region, but it may or may not actually be present at the specific area requiring clean-up. This would depend upon what the most recent use for the site has been.

The major soil groups of the world are summarized in this section. In addition, they and the soil subgroups found in the United States are described in detail in Appendix C. These are soil generalizations only; data specific to the site being remediated should be collected before a best-fit sensor selection can be made.

3.3.1. Major Soil Groups throughout the World

There are only eleven major soil groups throughout the world, and they are described in Table 3.3.1.1. These soil groups are identified with the most extensive listed first, following in descending order to the least prevalent listed last. Each of these major groups are comprised of a varied number of subgroups which depict the characteristics of the main group but vary primarily as a function of climate and moisture. An example of this would be found when one compares cool, wet soils with warm dry soils of the same major group. In Table 3.3.1.1 the attempt was made to simplify the scientific definitions of the soil types and instead describe the characteristics which would have the greatest influence on sensor effectiveness. The scientific descriptions of these major soil subgroups and their primary subgroups are presented in Appendix C.

In the United States there are only 36 soil subgroups of the major eleven soils, and they are identified in Tables C 2 through C 10 in Appendix C. Although there is a more refined granularity that quantifies variations within the majority of these subgroups, these differences will generally not have a first-order effect on sensor performance and will be considered only on a site-specific case-by-case basis. There are no major subgroups for either the histosol or the miscellaneous soil groups.

3.3.2. Soil, Vegetation, and Terrain at Sites

The soil geology, land surface characteristics, and probable indigenous vegetation, along with the soil conductance in units of attenuation (dB/m), are presented in Table 3.3.2.1 for the initial RAC 1 site candidates. The soil geology for each site was derived by identifying the site location from Figure 3.3.2.1, the soil compilation chart depicting the distribution of the principal soils in the United States, obtained from "The National Atlas of the United States of America" published by the Department of the Interior - United Stated Geological Survey, 1970. (See Appendix B, References).

The probable vegetation at each site was developed similarly from Figure 3.3.2.2, Potential Natural Vegetation, obtained from the same reference. The soil conductivity was determined from Figure 2.2.3.2 in Section 2. These factors were considered to be the dominant influences in determining which sensors would be most effective in detecting and locating buried or nearly buried ordnance and explosive waste. Since these site characterizations were derived from map information rather than from extensive surveys of the individual sites, the soil attenuation listed in Table 3.3.2.1, may be different from the actual values. Data specific to the site being remediated should be collected before a best-fit sensor selection can be made.

Table 3.3.1.1. Definitions of Major Soil Groups

Alfisol	Soils commonly found in mild climates. They have a light colored surface layer that covers a subsurface layer of clay. They are usually moist but during the warm season of the year are dry part of the time.
Aridisol	Principal soils of deserts and other arid lands. They commonly have a sandy texture and are light colored. They are low in organic matter and are never moist as long as three consecutive months.
Entisol	New soils that have not been in place long enough to develop layers. These soils are found on recently exposed surfaces such as flood plains and sand hills.
Histosol	Wet organic (peat and muck) soils; they are usually saturated with water and do not drain well. They are soils in which the decomposition of plant residues ranges from highly decomposed to not decomposed and are acidic; formed in swamps and marshes.
Inceptisol	Soils that are often found in former valley flood plains and on other stable land surfaces where soil layers are developing. These soils are starting to form a subsurface layer of clay. These soils are usually moist, but during the warm season of the year some are dry part of the time.
Mollisol	Most fertile and productive soils, known for their dark, mineral-rich surface layer. This thick layer has large amounts of base nutrients and is full of humus.
Oxisol	Soils that are found mainly on weathered, or broken up land surfaces in tropical areas. This kind of soil has a subsurface layer full of iron and aluminum.
Spodosol	Soils are infertile and acidic and do not hold moisture well. They have a pale surface layer and a dark subsurface layer in which humus, iron, and aluminum have accumulated.
Ultisol	Soils that have a light-colored surface layer and a reddish clay subsurface layer full of iron and aluminum. Although similar to alfisols, ultisols are found in warmer regions. They are usually moist but some are dry part of the time during the warm season.
Vertisol	Contain large amounts of clay. They develop in climates of alternating wet and dry seasons. This kind of soil swells when wet and shrinks when dry, which causes cracking. They have wide, deep cracks when dry.
Misc.	Barren or nearly barren areas that are mainly rock, ice, or salt and some included soils.

Since the Yuma Proving Grounds is not a RAC 1 site, it was not included in the site tables. However, it is an active military area in southwestern Arizona adjacent to the Colorado River and ideally represents the southwestern environment. Its soil is very arid, as it is never moist for as long as three consecutive months, and has a loamy layer of clay and hardpan. Its rough, rocky surface varies from nearly flat to moderately steep, jagged hills, all with sparse vegetation of chaparral and various species of cactus. The soil attenuation at Yuma is approximately 3 dB/m.

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	WARM SOILS Mean annual soil temperature higher than about 47°F			COOL SOILS Mean annual soil temperature lower than about 47°	
	MOIST	WET	DRY	MOIST	WET
ALFISOLS	Udalfs A6[1] A7[1] A8	Aqualfs A1 A2	Ustalfs A9 A10 Xeralfs A11 A12 A13	Boralfs A3 A4 A5	
ARIDISOLS			Argids D1 D2 D3 D4 Orthids D5 D6		
ENTISOLS	Psamments Quartzipsamments E10 Udipsamments E12[1]	Aquents E1	Fluvents E2 Orthents E3 E4 E5 E6 E7 E8 Psamments Torripsamments E11 Ustipsamments E13 Xeropsamments E14	Psamments Cryopsamments E9	
HISTOSOLS		H2			H1
INCEPTISOLS	Andepts Dystrandepts I2 Ochrepts Dystrochrepts I8 Eutrochrepts I9 Fragiochrepts I10 Tropepts I12 Umbrepts Haplumbrepts I14	Aquepts Haplaquepts I5 Humaquepts I6	Andepts Eutrandepts I3 Ochrepts Ustochrepts I11	Andepts Cryandepts I1 Ochrepts Cryochrepts I7 Umbrepts Cryumbrepts I13	Aquepts Cryaquepts I4
MOLLISOLS	Udolls M6 M7 M8	Aquolls M1 M2[1]	Ustolls M9 M10 M11 M12 M13 M14 Xerolls M15 M16	Borolls M3 M4 M5	
OXISOLS	Orthox O1		Ustox O2		
SPODOSOLS		Aquods S1		Orthods S2 S3 S4[2]	
ULTISOLS	Humults U2 U3 Udults U4 U5 U6	Aquults U1	Xerults U7		
VERTISOLS	Uderts V1 V2		Usterts V3 V4 Xererts V5		
Misc land types	X2 X4		X1 X5	X3	

[1]Includes some soils that are cool [2]Includes some soils that are warm

Legend 1 Enlarged Legend for Figure 3.3.2.1

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(1)

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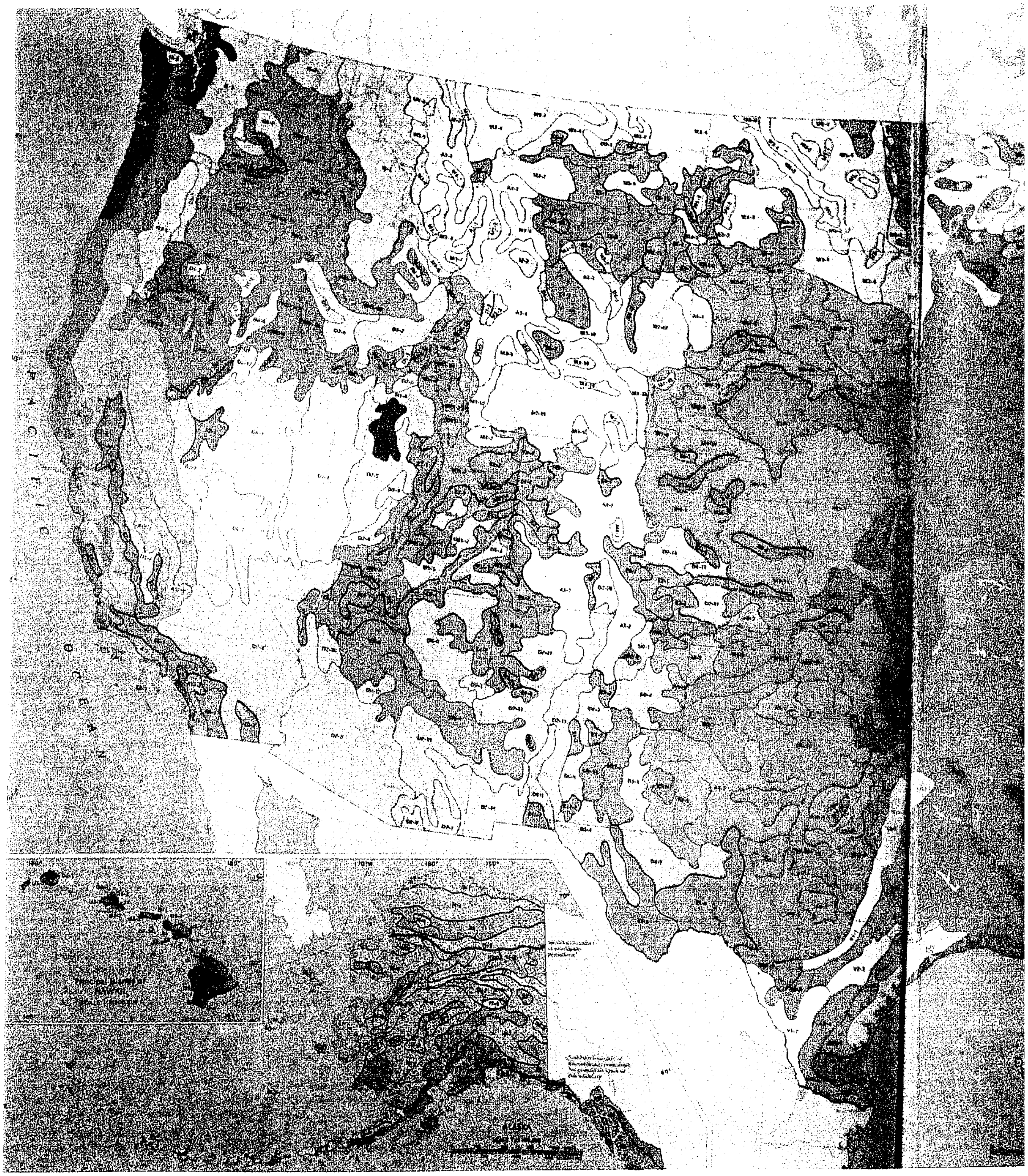

Figure 3.3.2.1. Distribution o

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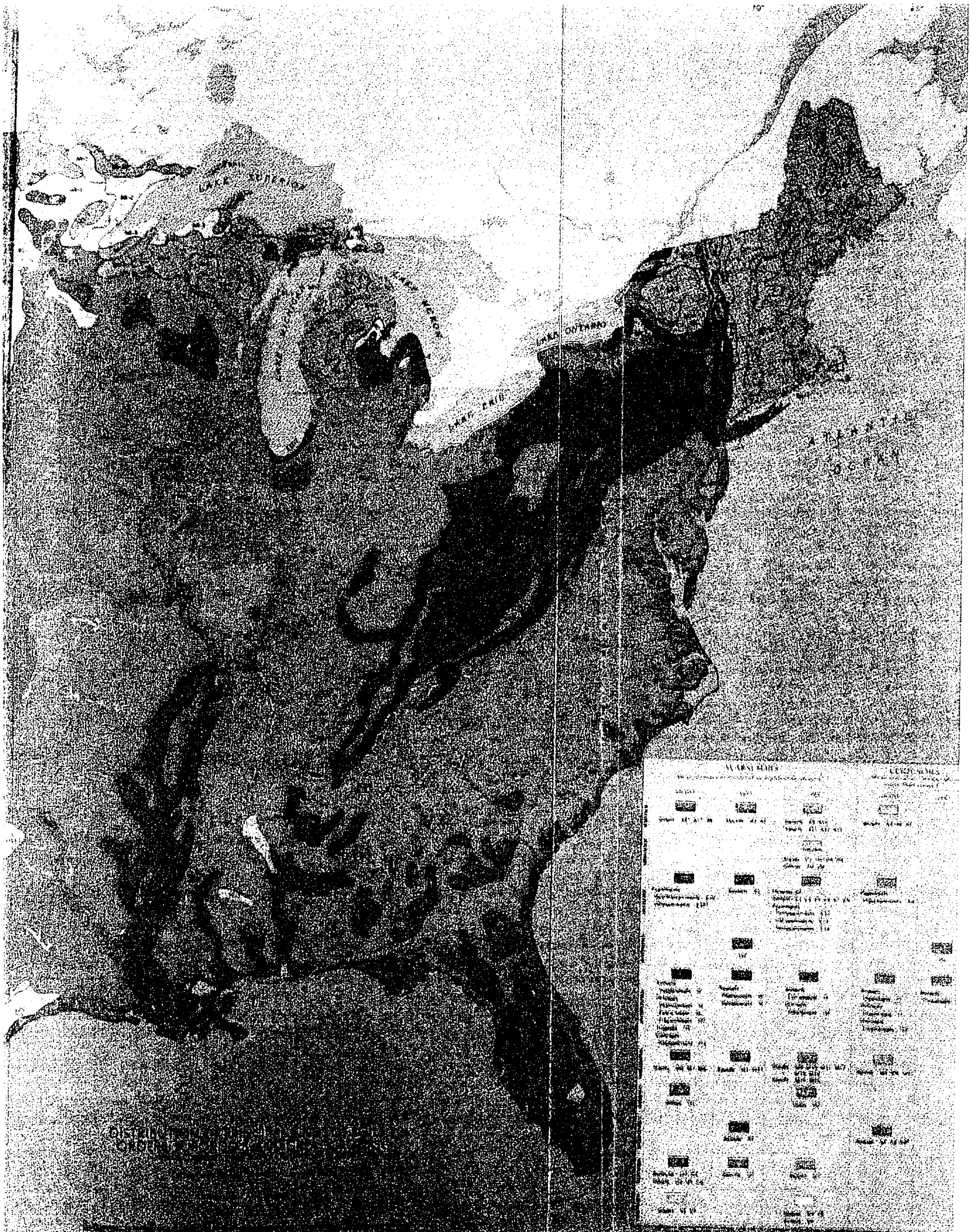
(2)



stribution of Principle Kinds of Soils, Orders, and Suborders

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WESTERN FORESTS

NEEDLELEAF FORESTS

- Spruce-cedar-hemlock forest (*Picea-Thuja-Tsuga*)
- 2 Cedar-hemlock-Douglas fir forest (*Thuja-Tsuga-Pseudotsuga*)
- 3 Silver fir-Douglas fir forest (*Abies-Pseudotsuga*)
- 4 Fir-hemlock forest (*Abies-Tsuga*)
- Mixed conifer forest (*Abies-Pinus-Pseudotsuga*)
- Redwood forest (*Sequoia-Pseudotsuga*)
- 7 Red fir forest (*Abies*)
- 8 Lodgepole pine-subalpine forest (*Pinus-Tsuga*)
- Pine-cypress forest (*Pinus-Cupressus*)
- 10 Western ponderosa forest (*Pinus*)
- 11 Douglas fir forest (*Pseudotsuga*)
- 12 Cedar-hemlock-pine forest (*Thuja-Tsuga-Pinus*)
- 13 Grand fir-Douglas fir forest (*Abies-Pseudotsuga*)
- 14 Western spruce-fir forest (*Picea-Abies*)
- Eastern ponderosa forest (*Pinus*)
- Black Hills pine forest (*Pinus*)
- 17 Pine-Douglas fir forest (*Pinus-Pseudotsuga*)
- 18 Arizona pine forest (*Pinus*)
- 19 Spruce-fir-Douglas fir forest (*Picea-Abies-Pseudotsuga*)
- 20 Southwestern spruce-fir forest (*Picea-Abies*)
- 21 Juniper-pinyon woodland (*Juniperus-Pinus*)

BROADLEAF FORESTS

- Oregon oakwoods (*Quercus*)
- 23 Mesquite bosques (*Prosopis*)

BROADLEAF AND NEEDLELEAF FORESTS

- Mosaic of numbers 2 and 22
- 25 California mixed evergreen forest (*Quercus-Arbutus-Pseudotsuga*)
- California oakwoods (*Quercus*)
- 27 Oak-juniper woodland (*Quercus-Juniperus*)
- 28 Transition between 27 and 31

- *Juniperus spp.* (juniper, red cedar)
- *Sequoia wellingtonia* (giant sequoia)
- *Yucca brevifolia* (Joshua tree)

WESTERN SHRUB AND GRASSLAND

SHRUB

- 29 Chaparral (*Adenostoma-Arctostaphylos-Ceanothus*)
- 30 Coastal sagebrush (*Salvia-Eriogonum*)
- 31 Mountain mahogany-oak scrub (*Cercocarpus-Quercus*)
- 32 Great Basin sagebrush (*Artemisia*)
- 33 Blackbrush (*Coleogyne*)
- 34 Saltbush-greasewood (*Atriplex-Sarcobatus*)
- 35 Creosote bush (*Larrea*)
- Creosote bush-bur sage (*Larrea-Franseria*)
- Palo verde-cactus shrub (*Cercidium-Opuntia*)
- 38 Ceniza shrub (*Leucophyllum-Larrea-Prosopis*)
- 39 Desert: vegetation largely absent

GRASSLAND

- 40 Fescue-oatgrass (*Festuca-Danthonia*)
- 41 California steppe (*Stipa*)
- 42 Tule marshes (*Scirpus-Typha*)
- 43 Fescue-wheatgrass (*Festuca-Agropyron*)
- 44 Wheatgrass-bluegrass (*Agropyron-Poa*)
- 45 Alpine meadows and barren (*Agrostis, Carex, Festuca, Poa*)
- 46 Fescue-mountain muhly prairie (*Festuca-Muhlenbergia*)
- 47 Grama-galleta steppe (*Bouteloua-Hilaria*)
- 48 Grama-tobosa prairie (*Bouteloua-Hilaria*)

SHRUB AND GRASSLAND COMBINATIONS

- 49 Sagebrush steppe (*Artemisia-Agropyron*)
- 50 Wheatgrass-needlegrass shrubsteppe (*Agropyron-Stipa-Artemisia*)
- 51 Galleta-three awn shrubsteppe (*Hilaria-Aristida*)
- 52 Grama-tobosa shrubsteppe (*Bouteloua-Hilaria-Larrea*)
- 53 Trans-Pecos shrub savanna (*Flourensia-Larrea*)
- 54 Mesquite-acacia-savanna (*Andropogon-Setaria-Prosopis-Acacia*)
- 55 Mesquite-live oak savanna (*Andropogon-Prosopis-Quercus*)

CENTRAL AND EASTERN GRASSLANDS

GRASSLAND

- 56 Foothills prairie (*Agropyron-Festuca-Stipa*)
- 57 Grama-needlegrass-wheatgrass (*Bouteloua-Stipa-Agropyron*)
- 58 Grama-buffalo grass (*Bouteloua-Buchloë*)
- 59 Wheatgrass-needlegrass (*Agropyron-Stipa*)
- 60 Wheatgrass-bluestem-needlegrass (*Agropyron-Andropogon-Stipa*)
- 61 Wheatgrass-grama-buffalo grass (*Agropyron-Bouteloua-Buchloë*)
- 62 Bluestem-grama prairie (*Andropogon-Bouteloua*)
- 63 Sandsage-bluestem prairie (*Artemisia-Andropogon*)
- 64 Shinnery (*Quercus-Andropogon*)
- 65 Northern cordgrass prairie (*Distichlis-Spartina*)
- 66 Bluestem prairie (*Andropogon-Panicum-Sorghastrum*)
- 67 Nebraska Sandhills prairie (*Andropogon-Calamovilla*)
- 68 Blackland prairie (*Andropogon-Stipa*)
- 69 Bluestem-sacahuista prairie (*Andropogon-Spartina*)
- 70 Southern cordgrass prairie (*Spartina*)
- 71 Palmetto prairie (*Serenoa-Aristida*)

GRASSLAND AND FOREST COMBINATIONS

- 72 Oak savanna (*Quercus-Andropogon*)
- 73 Mosaic of numbers 66 and 91
- 74 Cedar glades (*Quercus-Juniperus-Sporobolus*)
- 75 Cross timbers (*Quercus-Andropogon*)
- 76 Mesquite-buffalo grass (*Bouteloua-Buchloë-Prosopis*)
- 77 Juniper-oak savanna (*Andropogon-Quercus-Juniperus*)
- 78 Mesquite-oak savanna (*Andropogon-Prosopis-Quercus*)
- 79 Fayette prairie (*Andropogon-Buchloë*)
- Blackbelt (*Liquidambar-Quercus-Juniperus*)
- 81 Live oak-sea oats (*Quercus-Uniola*)
- 82 Cypress savanna (*Taxodium-Mariscus*)
- 83 Everglades (*Mariscus and Magnolia-Persea*)

Legend 2 Enlarged Legend for Figure 3.3.2.2 (Next page)

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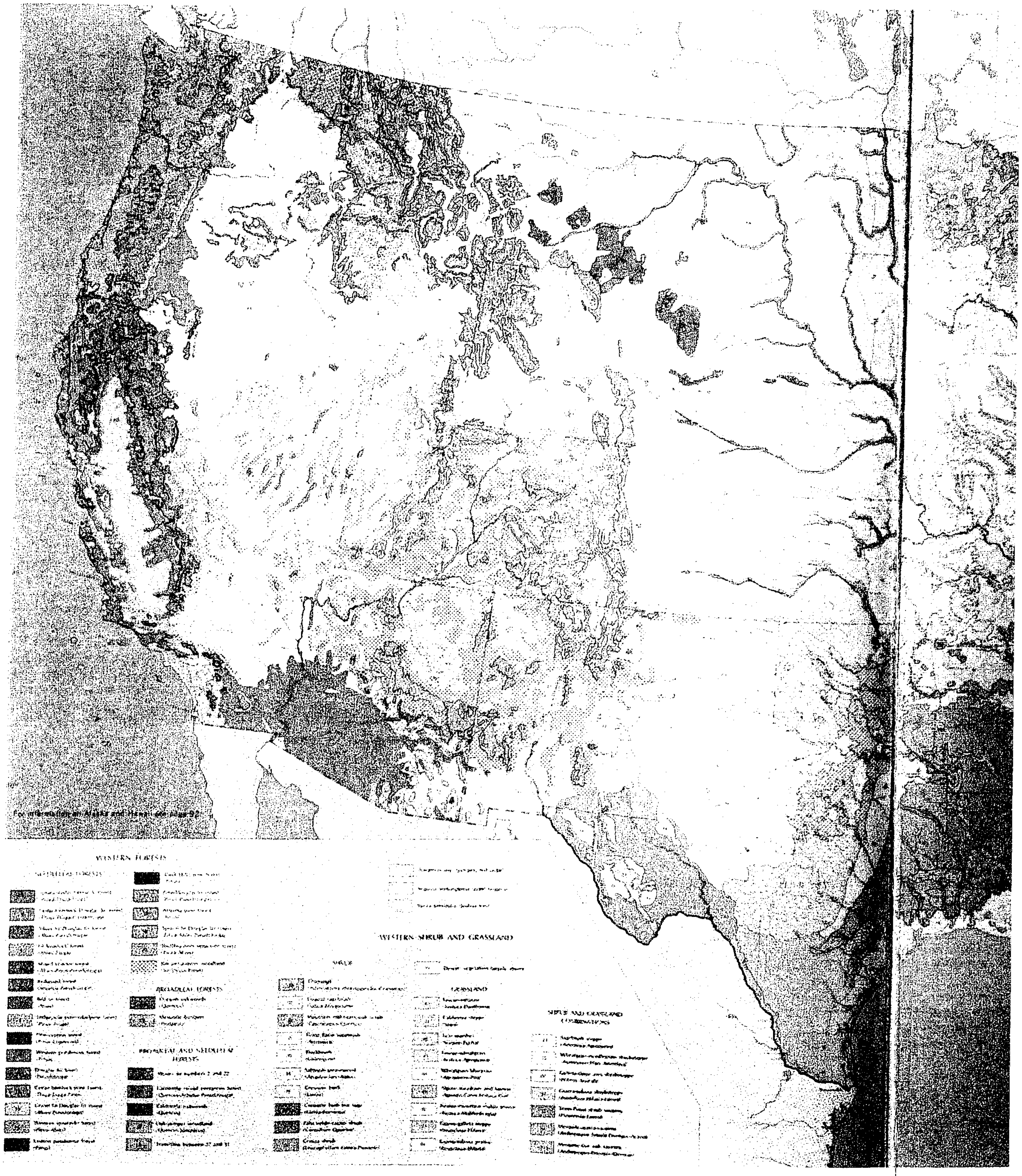

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2

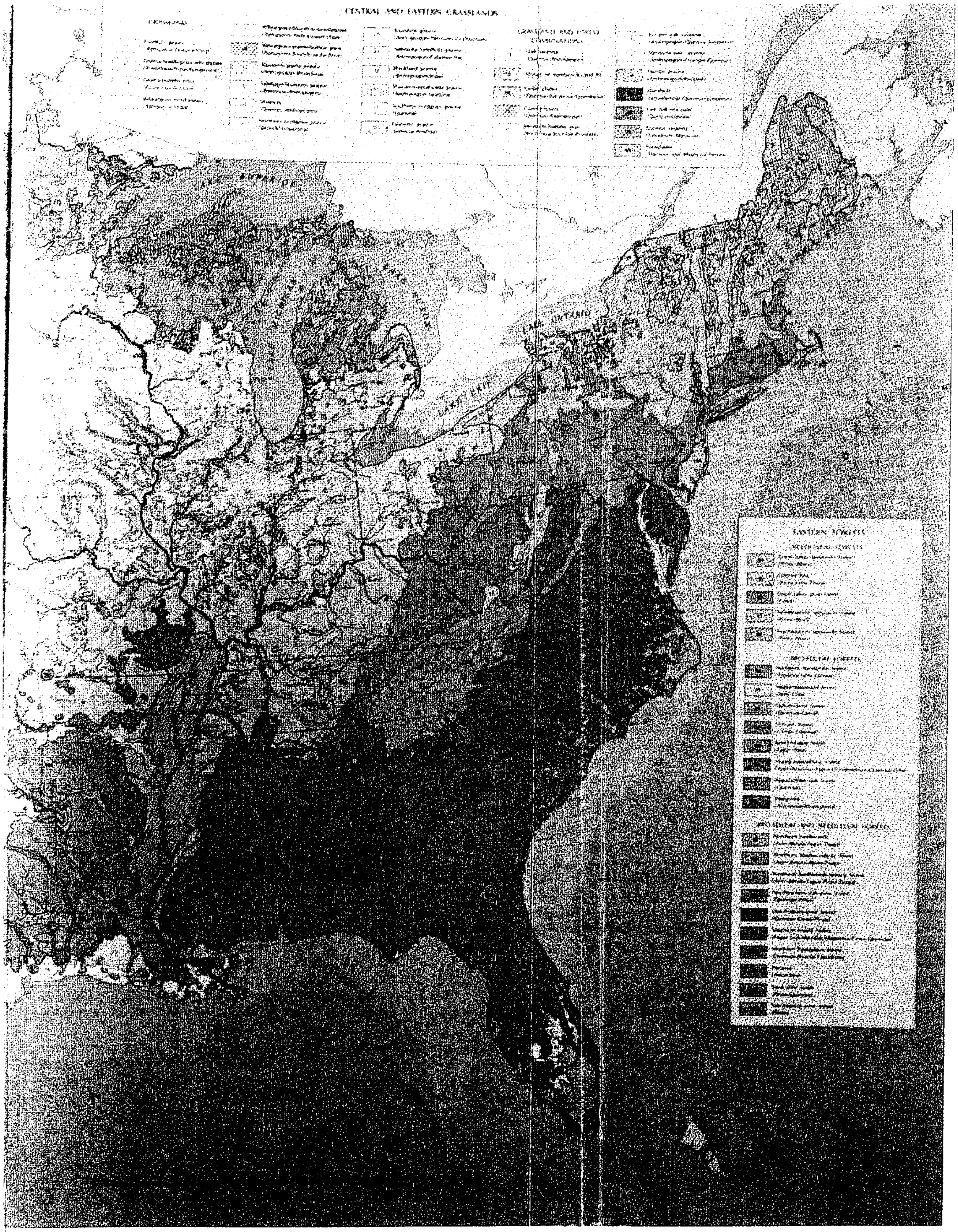

Figure 3.3.2.2. Potential Natural Vegetation

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EASTERN FORESTS

NEEDLELEAF FORESTS

84	Great Lakes spruce-fir forest *(Picea-Abies)*
85	Conifer bog *(Picea-Larix-Thuja)*
86	Great Lakes pine forest *(Pinus)*
87	Northeastern spruce-fir forest *(Picea-Abies)*
88	Southeastern spruce-fir forest *(Picea-Abies)*

BROADLEAF FORESTS

89	Northern floodplain forest *(Populus-Salix-Ulmus)*
90	Maple-basswood forest *(Acer-Tilia)*
91	Oak-hickory forest *(Quercus-Carya)*
92	Elm-ash forest *(Ulmus-Fraxinus)*
93	Beech-maple forest *(Fagus-Acer)*
94	Mixed mesophytic forest *(Acer-Aesculus-Fagus-Liriodendron-Quercus-Tilia)*
95	Appalachian oak forest *(Quercus)*
	Mangrove *(Avicennia-Rhizophora)*

BROADLEAF AND NEEDLELEAF FORESTS

97	Northern hardwoods *(Acer-Betula-Fagus-Tsuga)*
98	Northern hardwoods-fir forest *(Acer-Betula-Abies-Tsuga*
99	Northern hardwoods-spruce forest *(Acer-Betula-Fagus-Picea-Tsuga)*
100	Northeastern oak-pine forest *(Quercus-Pinus)*
	Oak-hickory-pine forest *(Quercus-Carya-Pinus)*
102	Southern mixed forest *(Fagus-Liquidambar-Magnolia-Pinus-Quercus)*
103	Southern floodplain forest *(Quercus-Nyassa-Taxodium)*
104	Pocosin *(Pinus-Ilex)*
105	Sand pine scrub *(Pinus-Quercus)*
106	Sub-tropical pine forest *(Pinus)*

Legend 3 Enlarged Legend for Figure 3.3.2.2 (Previous page)

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Table 3.3.2.1. General Site Conditions

Map Location†	State	Site	Soil Geology	Terrain and Surface Conditions	Probable Vegetation	Soil Atten. (dB/m)
1	AL	Camp Siebert Gun Range	Thick layer of clay without appreciable weatherable materials; usually moist; short or no dry periods	Rural/urban area; rolling hills; several creeks nearby	Oak-hickory-pine forest	0.7 - 1.3
2	CA	Camp San Luis Obispo	Dry summers; thick clay; loamy sand; layers hardened by carbonate	Rolling to moderately steep hills with rocky outcroppings; several arroyos in area	Grassy with chaparral and Calif. oakwoods	3.0
3	CA	Camp Elliot Air Field	Dry summers; thick clay; loamy sand; layers hardened by carbonate	Moderately flat rural setting surrounded by urban population center; small hills adjacent	Grassy	1.3 - 3.0
4	CA	CPSLO-Ernest Vollmer, Jr.	Dry summers; thick clay; loamy sand; layers hardened by carbonate	Rolling to moderately steep hills with rocky outcroppings; several arroyos in area	Grassy with chaparral and Calif. oakwoods	3.0
5	CA	Santa Rosa AAF Station	Rainy winters, dry summers; thin clay surface layer; some clay soils with deep cracks when dry	Flat to moderately rolling hills; some rocky outcroppings	Grassy with chaparral and Calif. oakwoods	3.0 - 5.0
6	DC	Spring Valley Air Field	Moist soil with relatively thin subsurface strata of clay; some crystalline clay materials	Flat urban area with much housing development	Cleared area with occasional oak-hickory-pine	1.3
7	GA	Mustard Gas Burial Site	Relatively thin subsurface layer of clay; usually moist with short or no dry periods	Rolling hills with creeks and ponds	Oak-hickory-pine forest	0.7 - 1.3
8	GN	War in Pacific-Guamsea	Volcanic	Hilly to mountainous	Subtropical	(data un-available)
9	IN	Camp Atterbury (Ammo Plant)	Usually moist but dry for short periods during warm season; some but relatively thin subsurface clay strata	Manufacturing facility with rail and road spurs; flat to gently sloping	Beech-maple	3.0
10	IL	Camp Grant Rifle Range Edison Park	Clay accumulations below surface; organic rich; usually moist	Generally flat to gently rolling	Prairie grass to oak hickory forest	3.0
11	HI	Heeia Combat Training Camp	Barren or nearly barren area; rocky plus rough broken land; volcanic	Rough rocky terrain surrounded by population center; gently sloping to steep	Sparse to tropical	(data un-available)

† Location identifier for Figure 3.2.1.1.

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Table 3.3.2.1 - General Site Conditions

Map Loca-tion	State	Site	Soil Geology	Terrain and Surface Conditions	Probable Vegeta-tion	Soil Atten. (dB/m)
12	MA	Camp Wellfleet Field	Cool soil; sandy; homogeneous; some iron and aluminum accumulation	Urban/rural seaport area; relatively flat; some marshes	Oak-pine	0.7
13	MA	Butler Point Battery Burial Site	Cool soil; sandy; homogeneous; some iron and aluminum accumulation	Beach area; flat to gently sloping	Sparse to oak-pine	0.7
14		[Site deleted from list]				
15	MD	Johns Hopkins University	Thin clay below surface; usually moist	Urban area; relatively flat	Cleared fields to oak-hickory-pine	1.3
16	MI	Camp Clayban AAA Firing Range	Cool soil; sandy and homogeneous; underlying strata of clay accumulations	Beach area with feeder roads; flat; some small streams/rivers	Beach grass and pine	0.7
17	MI	Ft. Custer Rec Red Arkapo	Usually moist but dry for short periods during warm season; some subsurface strata of clay	Rural; relatively flat to gently sloping	Oak-hickory	0.7
18	MO	Tyson Valley Powder Farm	Usually moist but dry for short periods during warm season; relatively thin clay strata; dense brittle strata below clay	Flat to gently sloping; surrounded by rolling hills; river adjacent	Oak-hickory	5.0
19	MS	Gulfport Army Air Field	Seasonally wet; relatively homogeneous; thin-to-thick clay strata	Relatively flat surrounded by urban population center; possibly marshy	Clearings to southern mixed forest	0.7
20	MS	Camp Shelby Maneuver Area	Usually moist; thick clay to loamy fine sand	Relatively flat to rolling hills; possibly marshy	Southern mixed forest	0.7
21	NC	Camp MacKallin	Usually moist soil; strata of thick clay with quartz formations	Relatively flat to slightly rolling hills; adjacent to several creeks and ponds	Oak-hickory-pine	0.7
22	NC	Charlotte Naval Ammunition Depot	Relatively thin clay below surface; usually moist	Urban area; flat to gently sloping	Clearings to oak-hickory-pine	0.7
23	NC	Laurinburg-Maxton ABO Fac	Thick clay strata; usually moist	Airport adjacent urban area; flat to gently sloping	Clearings to oak-hickory-pine	0.7
24	NE	Sioux Army Depotage Houma (24)	Relatively thin subsurface clay strata; shallow loam; semiarid	Flat to gently sloping open area adjacent to small town population center	Buffalo grass	3.0

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Table 3.3.2.1 - General Site Conditions

Map Location	State	Site	Soil Geology	Terrain and Surface Conditions	Probable Vegetation	Soil Atten. (dB/m)
25	NE	McCook Army AF Station	Semiarid; sublayers of salts or carbonates; relatively thin layer of clay; relatively homogeneous	Flat open area	Wheat grass-bluestem-needle grass	5.0
26	NJ	Ft. Hancock Rifle Range	Usually moist; sandy/grassy; some crystalline clay materials	Urban coastal area; flat to gently sloping	Grassy-oak	1.0
27	NY	Sampson Air Field	Usually moist but intermittently dry during warm season; relatively thin subsurface clay strata	Flat to gently sloping; scattered creeks; lake shoreline; considerable rail marshaling	Beech-maple-some oak	1.3
28	SC	Camp Croft Powder Farm	Usually moist; relatively thin subsurface clay layer	Rolling hills; military population center	Oak-hickory-pine	0.7
29	SC	Lake Murray Bombing Range	Usually moist; thin to moderate subsurface clay layer with some quartz formations	Rolling hills with rocky outcroppings	Oak-hickory-pine	1.3
30	TX	Dalhart AAFCHY Amphib. Base	Intermittently dry for long periods during warm season; some relatively thin subsurface of clay; hard strata of carbonates	Flat to gently sloping; open area; lake shore environment	Buffalo grass	5.0
31	VA	Buckroe Beach Sta #27	Seasonally wet; some subsurface clay strata with some iron-manganese; tidal marsh	Urban coastal environment; flat	Open with possible oak-hickory-pine	0.7 - 1.3
32	VI	Former Fort Segarra Island	Volcanic	Hilly to mountainous	Subtropical	(data unavailable)

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In order to get a better feel for the site conditions that may be expected, some representative site characteristics have been extracted from Table 3.3.2.1 and summarized below.

Table 3.3.2.2. Summary of Representative Site Characteristics

Characteristic	Occurrences
Urban/nearly urban	13
Forested	13
Grassy/chaparral	10
Cleared/sparse	9
Thin clay	18
Thick clay	10
Sandy/loamy	7
Volcanic	3
Flat to gently sloping	23
Hilly/mountainous	9
High water table	17
Saltwater coastline	6
Freshwater coastline	4
Wet/marshy	2
Semiarid	7
Soil attenuation 0.7 - 1.3	14
Soil attenuation 1.3 - 3.0	6
Soil attenuation 3.0 - 5.0	9

3.4. SUMMARY OF SENSOR CAPABILITIES

In Table 3.4.1 below, each of the sensors identified in Section 2 are organized by their generic classes as a function of four parameters: 1) Ideal Application, 2) Ideal Performance, 3) Impediments to Application, and 4) Degree of Impediment. The capabilities of each sensor are then summarized in a manner to allow a user the greatest ease of evaluating the potential applications of each to a specific site. For ideal conditions, each sensor would be expected to deliver its ideal performance. Because of the nature of the task of detecting and locating OEW in a real-world environment, there will naturally be impediments to this ideal. Some of these impediments will merely result in a loss of performance to a greater or lesser degree, while others are "binary" where the issue is whether the sensor is even capable of performing the function. An example of a binary impediment is a magnetometer's inability to detect non-ferrous objects. The degree of performance loss is reflected in the table, whereas the space is left blank for binary impediments. The information in Table 3.4.1 will serve to identify the effectiveness of any given sensor with the specific needs for each site.

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Table 3.4.1. Sensor Capabilities Summary

Sensor	Ideal Application	Ideal Performance	Impediments to Application	Degree of Impediment
Proton Precession Magnetometer	Land-based Hand-held Ferrous Metal OEW detection	Large ferrous objects detection	• nonferrous • small shells • deeply buried • magnetic rock environment • Long integration time	• to a fraction of a meter • on order of seconds
Optically Pumped Atomic Magnetometer	Land-based Airborne Ferrous Metal OEW detection	• Large and small types of OEW detection • 10 meter penetration depth in non-ferrous soil	• Not man-portable • 1-axis only • Cannot be used for non-ferrous detection	30-foot resolution when airborne
Single-Axis Fluxgate Magnetometer	Land-based, Airborne Ferrous Metal OEW detection	• Large and small types of OEW detection • Very compact and lightweight • Depths from 1-10 meter penetration in non-ferrous soil	• Cannot detect non-ferrous • Susceptible to high magnetic noise interference	situation-dependent
3-Axis Fluxgate Magnetometer	Land-based Airborne Ferrous Metal OEW detection	• Can detect size and depth to limited degree • Depths from 1-10 meter penetration in non-ferrous soil • Man-portable	• Cannot detect non-ferrous • Susceptible to high magnetic noise interference	situation-dependent
Fiber-Optic Magnetometer	Land-based Airborne Ferrous Metal OEW detection	Measure large and small types of OEW • 1-3-axis configurations feasible Depths from 1-10 meters penetration in non-ferrous soils • Hand-held	• Cannot detect nonferrous • Promising but immature technology	situation-dependent
Overhauser Effect Magnetometer	[fill in rest from PPM]	Faster integration time (in ms range)	Single-axis device	situation-dependent

Table 3.4.1 - Sensor Capabilities Summary

Sensor	Ideal Application	Ideal Performance	Impediments to Application	Degree of Impediment
SQUID Magnetometer	Land-based and Airborne Ferrous Metal OEW detection	• Measure large and small types of OEW with depth up to 120 ft • 3-axis feasible • Can detect size and depth to limited degree • Depths from 1-10 meter penetration in non-ferrous soil	• 4K cooling required • Transportable -- too large to easily hand-carry • Cannot detect nonferrous materials	For helicopter 100 ft. off ground, resolution might be to square meter.
Electromagnetic Induction	• Shallow buried nonferrous and ferrous OEW • land-based	• up to 1m depth in any soil	• Limited to shallow depths; less than 1m	Degree of impediment 1m. • Too strong a probing signal may detonate OEW.
Airborne EM sensor	Identify clusters of ordnance in homogenous soil.	Locate clusters of OEW by identifying ground conductance change.	Low ground resolution	Pixel size on order of 1 pixel = 100m.
Narrow-Band land-based GPR	Vertical-profiler • smooth terrain OEW detection in dry sand, ice, low salinity water table • ground-towed	20-100 meter depth	Performs poorly in high-conducting soils, mineralogical clay soils, and salt water. Further impediments are heavy brush, RF noise sources, etc.	• poor penetration in clay: <1m • In Water: <3m • Low range resolution: >1m.
Ultra-wideband GPR	• Good for both Vertical-profiler and SAR • Land-based or airborne low salinity water table good image and range resolution • High spatial and range resolution	20-100 meter depth	Performs poorly in high-conducting soils, mineralogical clay soils, and salt water. Further impediments are heavy brush, RF noise sources, etc.	• poor penetration in clay: <1m • In Water: <3m
Airborne GPR	• Same as other GPR • large swath width • rapid large area coverage	• Capable of SAR 1x1 m resolution from 3000'. • vertical profiler from 20-100 meter depth penetration	• Performs poorly in Clay soil, sea water • Large volume and weight of system	• poor penetration in clay: <1m • In Water: <3m

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Table 3.4.1 - Sensor Capabilities Summary

Sensor	Ideal Application	Ideal Performance	Impediments to Application	Degree of Impediment
Synthetic-Aperture GPR	• Same as other GPR • High resolution subsurface OEW detection	• Capable of SAR 1x1 m resolution from 3000 feet.	• Limited penetration because of moving platform • more exotic control and processing electronics • Performs poorly in Clay soil, sea water • Large volume and weight of system	• <1 m penetration
FM-CW GPR	• Same as other GPR • Large dynamic range • High signal-to-noise ration than ground-based or airborne systems	• Deeper penetration and better detection	• Exotic electronics timing and frequency control	situation-dependent
Harmonic GPR	• Metallic OEW detection via 3rd harmonic return • natural object and clutter rejection	• Detect OEW clusters with metallic joints, welds, etc.	• Low penetration; <5 meters • Need high transmitted power and receiver sensitivity	• Low resolution 20 x 40 m • Order of magnitude more power and sensitivity
Interferometric Impulse Radar	Good for ground and airborne 3-D imaging. • Superior object recognition	• Resolution down to 1/3 of wavelength • vertical profiler from 20-100 meter depth penetration	• Exotic post-processing hardware and algorithms • Technology immature.	Same limitations as other low-frequency GPR
Cone Penetrometer	All types of OEW within 3 meter radius of sensor's tip in borehole.	• Capable of detecting all types of OEW up to 3 m penetration • Low false alarm rate	• Requires a GPR, ground radio wave, or other techniques to locate OEW. • Very heavy machinery needed to insert sensor. • Penetrometer may detonate objects being sought.	• Limited to 3-meter radius of sensor. • Large vehicle cannot move fast (1 acre per day typical.)
Transient Acoustic	(See Acoustic Imaging)	—	—	—

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Table 3.4.1 - Sensor Capabilities Summary

Sensor	Ideal Application	Ideal Performance	Impediments to Application	Degree of Impediment
Seismic	Underground	Low-frequency (< 20 Hz)	Irregularity in compactness of the soil Difficulty in differentiation between the native stones and the ordnance in the soil	Requires a rather large seismic wave generator
Ultrasonic	Airborne and under water	High frequency (> 20,000 Hz)	Refracted sound waves in air-earth interface due to non uniformity of the densities of the two mediums in airborne application Data must be corrected to take care of temperature gradients, changes in density, reflection from surface and bottom of the sea, and other error-producing effects in underwater application.	"Robust" detection of ordnance may not be possible. Requires a large transducer to generate ultrasonic waves.
Acoustic Imaging	Underwater and land imaging	• High frequency (100 kHz) for surface imaging (no penetration) • low-frequency (20 kHz) for subsurface imaging	• slow sound wave restricts sensor moving speed • noisy image	• Low penetration at 20 kHz (<1m)
Visible Imaging	Surface mapping on a clear day with no vegetation.	Clear day, near range high resolution imaging from air	• Poor underwater imaging • Poor on foggy and rainy days • Poor OEW discrimination against natural background • Cannot differentiate rusty ordnance and soil.	• Underwater imaging down to 10 m for clear water (other water measured in inches)

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Table 3.4.1 - Sensor Capabilities Summary

Sensor	Ideal Application	Ideal Performance	Impediments to Application	Degree of Impediment
Infrared Radiometry	OEW detection via IR thermal imaging	surface and subsurface all types OEW detection	• Requires a sensitive IR detector • Requires adequate sunlight.	• Can detect millidegree K temperature changes • Subsurface penetration less than 4 inches.
MWIR Imaging Spectroscopy	Objects with heat capacity different from ground	NEDT = 0.05K	Deeply burial Inclement weather	major major
TIR Imaging Spectroscopy	Warm objects on cooling ground	NEDT = 0.01K	Deep burial Inclement weather	moderate moderate
Millimeter Wave Radiometry	OEW detection in rainy, foggy day	Surface OEW detection only	No subsurface detection.	major
2-D LIDAR	• Surface (land or underwater) OEW detection	• Polarization discrimination between man-made and natural objects (Polarimetrics) • All-weather, day/night operation • Blue-green laser for underwater operation	• Not good for buried object or in moderately vegetated area	major
3-D LIDAR (LADAR)	• Surface OEW detection • Toxic chemical agent and waste detection (detects if in vapor form)	• 3-D air and surface pollutants distribution and mapping	• Air or surface detection only, not good for buried or underwater objects	major
Line Spectra LIDAR (laser-induced Fluorescence LIDAR)	• Probe chemical or oil spill using UV or short wavelength laser, measure fluorescence response • Can detect explosive chemical stains in soils	• Perfect for oil spilled oil and chemical agent	• Limited to surface object	major for surface objects

Table 3.4.1 - Sensor Capabilities Summary

Sensor	Ideal Application	Ideal Performance	Impediments to Application	Degree of Impediment
Nuclear Technology	• Non-metallic ordnance	• Ideal for detecting shallow, non-metallic buried ordnance.	• Heavy vehicle required for transporting radiation generator. • Remote operation required due to dangerous radiation levels • Performance impeded by thick metal casings.	• < 10 cm penetration
Electron Tunneling magnetometer	Land-based Airborne Ferrous Metal OEW detection	Extremely light weight, small volume, high sensitivity • Handheld, multi-axis magnetometer array possible.	• Immature technology	unknown

3.5. ASSESSMENT OF SENSOR TECHNOLOGY APPLICABLE TO SITE NEEDS

In an attempt to assess the effectiveness of the various sensors within the suite identified for detecting and locating buried or partially buried ordnance, the sensor capabilities described in Table 3.4.1 were superimposed onto the site conditions for the RAC 1 sites depicted in Table 3.3.2.1. Judgments were then made regarding the applicability of the sensors to the specific site geological, environmental, and vegetation conditions. The estimated effectiveness of each of these sensors at each site is presented in Tables 3.5.1 through 3.5.3 below. Since these site characterizations were derived from map information rather than from extensive surveys of the individual sites, the recommendations appearing in Tables 3.5.1 through 3.5.3 should be treated as a first-generation assessment. Data specific to the site being remediated should be collected before a best-fit sensor selection can be made.

Ideally, before one can develop a more accurate assessment of expected sensor effectiveness, one needs to know beforehand the probable type or class of OEW being sought at a specific site; for example, impacted artillery rounds, buried munitions, or dispersed chemicals. Since this information was not readily available when Tables 3.5.1 through 3.5.3 were generated, the assumption was made that the OEW was buried or partially buried in various forms of "munition-like" containment. Partially buried also implies some discernible residual disturbance to the soil surface different from the natural surroundings that could have been caused by munition impact. Because of this assumption, the soil geology was a dominant factor in the sensor assessment depicted in the tables below. Reference to "ferrous", implies anything constructed predominantly of iron. Each of the entries are ranked visually. Icons are defined below each table. The meanings of the definitions appear below:

● **Most Applicable** - under the given conditions, these technologies will provide the best performance in their respective areas.

◒ **Average** - this technology will work adequately under the stated conditions, although there are other technologies reviewed herein that will perform the job faster, with greater sensitivity, from greater distances, or with fewer false alarms.

○ **Poor** - under the stated conditions, this technology is not recommended to be used for the detection and location of OEW.

This data is based upon a thorough understanding of the theoretical limits and strengths of differing sensor technologies, and is not necessarily indicative of the quality of a vendor's implementation. These ranking symbols represent a combination of relative values and absolute ratings. When two sensor types are ranked differently, it can be interpreted to mean that the higher-ranked sensor will perform better on the indicated ordnance type than will the lower-ranked sensor. If no sensor will adequately locate an ordnance type, none are ranked highly.

Table 3.5.1. Assessment of Sensor Technology Capable of Detecting Only Ferrous OEW*

Site Number	State	Site Location	Proton Presession Magnetometer	Single-Axis Fluxgate Magnetometer	3-Axis Fluxgate Magnetometer	Fiber-Optic Magnetometer	Overhauser Effect Magnetometer	SQUID Magnetometer	Electron Tunneling Magnetometer	Optically Pumped Magnetometer
1	AL	Camp Siebert Gun Range	◔	◒	◕	◕	◒	●	◕	◕
2	CA	Camp San Luis Obispo	◒	◒	◕	◕	◒	●	◕	◕
3	CA	Camp Elliot Air Field	◒	◒	◕	◕	◒	●	◕	◕
4	CA	CPSLO-Ernest Vollmer, Jr.	◒	◒	◕	◕	◒	●	◕	◕
5	CA	Santa Rosa AAF Station	◒	◒	◕	◕	◒	●	◕	◕
6	DC	Spring Valley Air Field	◔	◒	●	◕	◔	◕	◕	◕
7	GA	Mustard Gas Burial Site	◔	◒	◕	◕	◒	●	◕	◕
8	GN	War in Pacific-Guamsee	○	◔	◒	◒	◔	◕	◒	◒
9	IN	Camp Atterbury (Ammo Plant)	◔	◒	◕	◕	◒	●	◕	◕
10	IL	Camp Grand Rifle Range	○	◔	◒	◒	◒	●	●	◕
11	HI	Heeia Combat Training Camp	○	◔	◒	◒	◔	◕	◒	◒
12	MA	Camp Wellfleet Field	◒	◒	◕	◕	◒	●	◕	◕
13	MA	Butler Point Battery Burial Site	◒	◒	◕	◕	◒	●	◕	◕
14	MD	[Site deleted from list]								
15	MD	Johns Hopkins University	◒	◒	◕	◕	◒	●	◕	◕
16	MI	Camp Clayban AAA Firing Range	◒	◒	◕	◕	◒	●	◕	◕
17	MI	Ft. Custer Rec Red Arkapo	◔	◒	◕	◕	◒	●	◕	◕
18	MO	Tyson Valley Powder Farm	◔	◒	◕	◕	◒	●	◕	◕
19	MS	Gulfport Army Air Field	◒	◒	◕	◕	◒	●	◕	◕
20	MS	Camp Shelby Maneuver Area	◒	◒	◕	◕	◒	●	◕	◕
21	NC	Camp MacKallin	◔	◒	◕	◕	◒	●	◕	◕
22	NC	Charlotte Naval Ammunition Depot	◒	◒	◕	◕	◒	●	◕	◕
23	NC	Laurinburg-Maxton ABO Fac	◒	◒	◕	◕	◒	●	◕	◕
24	NE	Souix Army Depotage Houma	◒	◒	◕	◕	◒	●	◕	◕
25	NE	McCook Army AF Station	◒	◒	◕	◕	◒	●	◕	◕
26	NJ	Ft. Hancock Rifle Range	○	◔	◒	◒	◒	●	●	◕
27	NY	Sampson Air Field	◔	◒	◕	◕	◒	●	◕	◕
28	SC	Camp Croft Powder Farm	◔	◒	◕	◕	◒	●	◕	◕
29	SC	Lake Murray Bombing Range	◔	◒	◕	◕	◒	●	◕	◕
30	TX	Dalhart AAFCHY Amphib. Base	◒	◒	◕	◕	◒	●	◕	◕
31	VA	Buckroe Beach Sta #27	◒	◒	◕	◕	◒	●	◕	◕
32	VI	Former Fort Segarrak Island	○	◔	◒	◒	◔	◕	◒	◒
--	AZ	Yuma	◒	◒	◕	◕	◒	●	◕	◕
		Average	◔	◒	◕	◕	◒	●	◕	◕

Scale: ○ ◔ ◒ ◕ ●

Poor Average Most Applicable

* Note: Non-ferrous and chemical OEW will not be found.

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Table 3.5.2. Assessment of Sensor Technology Capable of Detecting Both Ferrous and Non-Ferrous Solid OEW*

Site Number	State	Site Location	Electromagnetic Induction	Airborne EM Sensor	Narrow-Band GPR (land)	Ultra-Wideband GPR (ground)	Airborne GPR	Synthetic-Aperture GPR (airborne)	FM-CW GPR	Harmonic GPR	Interferometric Impulse Radar	Cone Penetrometer	Transient Acoustic	Seismic	Ultrasonic	Acoustic Imaging	Nuclear Technology (Non-Metalic Only)
1	AL	Camp Siebert Gun Range	◔	○	○	◔	◔	◔	◔	○	○	◔	○	◔	○	◔	◔
2	CA	Camp San Luis Obispo	◔	○	◔	◔	◑	◑	◔	○	◔	○	○	○	◔	◔	◔
3	CA	Camp Elliot Air Field	◑	◔	◑	◑	◑	◑	◑	○	◔	◔	○	◔	◔	◔	◑
4	CA	CPSLO-Ernest Vollmer, Jr.	◑	○	◔	◔	◑	◑	◔	○	◔	○	○	○	◔	◔	◔
5	CA	Santa Rosa AAF Station	◔	○	◔	◔	◑	◑	◔	○	◔	○	○	○	◔	◔	◔
6	DC	Spring Valley Air Field	○	○	○	◔	○	○	○	○	○	○	○	○	○	○	◔
7	GA	Mustard Gas Burial Site	◔	○	○	○	○	◔	○	○	○	◔	○	◔	○	◔	◑
8	GN	War in Pacific-Guamsee	○	○	○	○	◑	◑	◔	○	◔	○	○	○	○	○	○
9	IN	Camp Atterbury (Ammo Plant)	◑	◔	◑	◑	◑	◔	◔	○	◔	◔	○	◔	◔	◔	◑
10	IL	Camp Grand Rifle Range	◑	◑	◔	◔	○	◔	○	○	○	○	○	○	○	○	◔
11	HI	Heeia Combat Training Camp	○	○	○	○	◑	◑	◔	○	◔	○	○	○	○	○	○
12	MA	Camp Wellfleet Field	○	◔	◑	◑	◔	◑	◑	○	◔	◔	○	◔	◔	◔	◑
13	MA	Butler Point Battery Burial Site	◑	◑	◑	◑	◕	◑	◑	◑	◔	◔	○	◔	◔	◔	◑
14	MD	[Site deleted from list]															
15	MD	Johns Hopkins University	◔	○	◔	◔	○	○	◔	○	◔	◔	○	◔	◔	◔	◑
16	MI	Camp Clayban AAA Range	◑	◔	◑	◑	◑	◕	◑	○	◔	◔	○	◔	◔	◔	◑
17	MI	Ft. Custer Rec Red Arkapo	◔	◔	○	○	◔	◔	◔	○	○	○	○	○	○	○	○
18	MO	Tyson Valley Powder Farm	◑	◔	◑	◑	◑	◔	◔	○	◔	◔	○	◔	◔	◔	◑
19	MS	Gulfport Army Air Field	◑	◔	◔	◔	◔	◔	○	○	○	◔	○	◔	◔	◔	◑
20	MS	Camp Shelby Maneuver Area	◑	◔	◔	◔	◑	◕	◔	○	○	◔	○	◔	◔	◔	◑
21	NC	Camp MacKallin	◔	◔	○	○	◑	◕	◔	○	○	◔	○	◔	○	◔	◔
22	NC	Charlotte Naval Ammo Depot	◑	○	◔	◔	○	○	◔	○	◔	◔	○	◔	◔	◔	◑
23	NC	Laurinburg-Maxton ABO Fac	◑	◔	◑	◑	◕	◕	◑	○	◔	◑	○	◑	◔	◑	◕
24	NE	Souix Army Depotage Houma	◑	◔	◑	◑	◑	◑	◑	○	◔	◔	○	◔	◔	◔	◑
25	NE	McCook Army AF Station	◑	◔	◔	◔	◔	◔	◔	○	○	◔	○	◔	◔	◔	◑
26	NJ	Ft. Hancock Rifle Range	◑	◔	◑	◑	○	○	◔	○	◔	◔	○	◔	◔	◔	◑
27	NY	Sampson Air Field	◑	◔	◑	◑	◕	◕	◑	○	◔	◔	○	◔	◔	◔	◑
28	SC	Camp Croft Powder Farm	◑	◔	◑	◑	◕	◕	◔	○	◔	◔	○	◔	◔	◔	◑
29	SC	Lake Murray Bombing Range	◑	◔	◑	◑	◕	◕	◔	○	◔	◔	○	◔	◔	◔	◑
30	TX	Dalhart AAFCHY Amphib. Base	◑	◔	◔	◔	◔	◔	◔	○	○	◔	○	◔	◔	◔	◑
31	VA	Buckroe Beach Sta #27	◔	○	◔	◔	○	○	◔	○	◔	◔	○	◔	◔	◔	◑
32	VI	Former Fort Segarrak Island	○	○	○	○	◑	◑	◔	○	◔	○	○	○	○	○	○
--	AZ	Yuma	◑	◑	◕	◕	●	●	◑	○	◑	◕	○	◕	◑	◕	◕
		Average	◔	◔	◔	◔	◑	◑	◔	○	◔	◔	○	◔	◔	◔	◑

Scale: ○ ◔ ◑ ◕ ●

Poor — Average — Most Applicable

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* Note: With the exception of Nuclear Technology, chemical OEW will not be found.

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Table 3.5.3. Assessment of Sensor Technology Capable of Detecting Solid and Gaseous OEW on the Ground Surface*

Site Number	State	Site Location	Visible Imaging	Infrared Radiometry	Infrared Imaging Spectrometry	Millimeter Wave Radiometry	2-D LIDAR	3-D LIDAR (LADAR)	Line Spectra LIDAR
1	AL	Camp Siebert Gun Range	○	○	○	○	○	◔	◔
2	CA	Camp San Luis Obispo	◔	○	○	○	○	◔	◔
3	CA	Camp Elliot Air Field	◑	◑	○	○	◔	◔	◔
4	CA	CPSLO-Ernest Vollmer. Jr.	◔	○	○	○	○	◔	◔
5	CA	Santa Rosa AAF Station	◔	○	○	○	○	◔	◔
6	DC	Spring Valley Air Field	○	○	○	○	○	◔	◔
7	GA	Mustard Gas Burial Site	○	○	◔	○	○	◑	◔
8	GN	War in Pacific-Guamsee	○	○	○	○	○	○	○
9	IN	Camp Atterbury (Ammo Plant)	○	○	◔	○	○	◔	◔
10	IL	Camp Grand Rifle Range Edison Pa	○	○	○	○	○	○	○
11	HI	Heeia Combat Training Camp	○	○	○	○	○	○	○
12	MA	Camp Wellfleet Field	◔	◑	○	○	◑	◔	◔
13	MA	Butler Point Battery Burial Site	◔	◑	○	○	◑	◔	◔
14	MD	[Site deleted from list]							
15	MD	Johns Hopkins University	○	○	○	○	○	◔	◔
16	MI	Camp Clayban AAA Firing Range	◔	◑	○	○	◑	◑	◑
17	MI	Ft. Custer Rec Red Arkapo	○	○	○	○	○	○	○
18	MO	Tyson Valley Powder Farm	○	○	○	○	○	◔	◔
19	MS	Gulfport Army Air Field	○	○	○	○	○	○	○
20	MS	Camp Shelby Maneuver Area	○	○	○	○	○	○	○
21	NC	Camp MacKallin	○	○	○	○	○	○	○
22	NC	Charlotte Naval Ammunition Depot	◔	◔	○	○	◔	◔	◔
23	NC	Laurinburg-Maxton ABO Fac	○	○	○	○	○	○	○
24	NE	Souix Army Depotage Houma	◔	◔	○	○	○	○	○
25	NE	McCook Army AF Station	○	○	○	○	○	○	○
26	NJ	Ft. Hancock Rifle Range	○	○	○	○	○	○	○
27	NY	Sampson Air Field	○	○	◔	○	○	◔	◔
28	SC	Camp Croft Powder Farm	○	○	○	○	○	◔	◔
29	SC	Lake Murray Bombing Range	○	○	○	○	○	◔	◔
30	TX	Dalhart AAFCHY Amphib. Base	○	○	○	○	○	○	○
31	VA	Buckroe Beach Sta #27	○	○	○	○	○	◔	◔
32	VI	Former Fort Segarrak Island	○	○	○	○	○	○	○
--	AZ	Yuma	◑	◑	◑	○	◕	◔	◔
		Average	○	○	○	○	○	○	○

Scale: ○ ◔ ◑ ◕ ●

Poor Average Most Applicable

* Note: Buried ordnance will generally not be found.

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3.6. SUMMARY AND COST-EFFECTIVENESS OF ASSESSMENT

The evaluations displayed in Tables 3.5.1 through 3.5.3 have been averaged and displayed to ascertain any apparent trends or deviations that might lend insight into probable sensor performance. Although each site is different, this process is an indication of how universally effective any given sensor might be. As can be seen, three technologies for the detection and location of OEW tend to dominate -- multiaxis magnetometers, airborne ground-penetrating radar, and nuclear activation technology. While other evolving technology is promising, there is considerable development yet remaining. The most important observation, however, is that there is no single technology that can accomplish this task unambiguously. For all their merits, neither magnetometers, GPR, nor nuclear activation applied alone can assure more than a modicum of success probability. While each is a powerful technology with distinct advantages, none has the breadth of capability to interpret all of the phenomena that are typically encountered in the search for OEW. This includes the capability to discriminate OEW from background artifacts, the ability to resolve individual entities below ground, and the ability to determine depth below the surface independent of geology.

The successful accomplishment of this task will be dependent upon "sensor fusion" whereby a discrete suite of sensors are selected and specialized to the requirements of a specific site. This suite most likely would consist of the three dominant technologies plus one or two others. The information gleaned from sensor fusion and signal processing would complement each other sufficiently that the vast majority of the OEW at the site can be readily identified for disposal.

The inherent cost associated with the fielding of any special instrumentation must also be addressed. Because of this, the cost-effectiveness of the sensor deployment must be considered in order to maximize the return. The maximum probability of success is strongly dependent upon primarily four parameters -- the maturity of the technology, its sensitivity at the target region, its resolution of the target objects, and its simplicity. However, any one of these features can and should be traded off with a more effective process. As an example, airborne sensors by their very nature will be more costly than those deployed along the ground. However, a much greater area can be covered more quickly from the air. If the primary objective were to detect the *approximate* location of *probable* OEW, then this could very well be accomplished more effectively by air. For this purpose, the added complexity can be traded off favorably with the greatly reduced time and hence cost.

Although somewhat beyond the scope of this report, the cost-effectiveness of the sensor deployment can be derived more rigorously. An outline of how this could be developed is presented below. First, a "standard" cost of deployment (CD) is created based on the experience of established practice. Cost of deployment would include such factors as the sensor procurement cost, any required adaptations, and the operations cost. This standard becomes the reference against which the deployment of other sensors is compared. The difference between the deployment cost of a new sensor and the standard can be related by the following equation:

$$\Delta(CD) = \partial(CD)/\partial(A)*\Delta A + \partial(CD)/\partial(B)*\Delta B + \ldots.$$

where:

CD = cost of deployment
A, B, ... = influencing parameters
$\partial()$ is the symbol for partial derivative

The partial derivative of the parameter being affected (the cost of deployment) with respect to the influencing parameter is referred to as the "influence coefficient". Influencing parameters can be factors such as improved sensitivity, better resolution, lighter weight, or reduced complexity. The resulting $\Delta(CD)$ is then added to the standard cost of deployment to establish the deployment cost of the new sensor as follows:

$$CD_{new} = CD_{std} + \Delta(CD).$$

It is very important to note that the sign of $\Delta(CD)$ can be either positive or negative. If there have been general improvements that have resulted in cost reductions, it will be negative and CD_{new} will be smaller than CD_{std}.

3.7. SUMMARY OF SENSOR TYPE RELEVANCE TO SITE CHARACTERISTICS

This section summarizes the applicability of different sensor classes to the various terrain types that are found among the RAC 1 sites reviewed. Each of the entries are ranked visually with icons, which are defined below the table. The meanings of the definitions appear below:

● **Most Applicable** - under the given conditions, these technologies will provide the best performance in their respective areas.

◒ **Average** - this technology will work adequately under the stated conditions, although there are other technologies reviewed herein that will perform the job faster, with greater sensitivity, from greater distances, or with fewer false alarms.

○ **Poor** - under the stated conditions, this technology is not recommended to be used for the detection and location of OEW.

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Table 3.7.1. Sensor Applicability to Site Characteristics

Sensor Technology	Urban/nearly urban	Forested	Grassy/chaparral	Cleared/sparce	Thin clay	Thick clay	Sandy/loamy	Volcanic	Flat to gently sloping	Hilly/mountainous	High water table	Saltwater coastline	Freshwater coastline	Wet/marshy	Semiarid/arid	Average
GPR - Land	◑	◔	◑	◕	◔	○	◕	◔	◕	○	○	○	◔	○	●	◔
GPR - Air	◔	◑	◕	◕	◔	○	●	◕	◕	◑	○	○	◑	◔	●	◑
EM - Land	◑	◔	◑	◑	◑	◑	◑	◔	◑	○	◑	○	◑	○	◑	◔
EM - Air	◔	◔	◔	◔	◔	◔	◔	◔	◔	○	◔	○	◔	◔	◔	◔
Magnetometer - Land	◕	●	●	●	●	●	●	◕	●	◑	●	●	●	◑	●	●
Magnetometer - Air	◑	◕	◕	◕	◕	◕	◕	◑	◕	◕	◕	◕	◕	◕	◕	◕
IR Radiometry - Land	○	○	○	◑	○	○	○	○	◔	○	○	◔	◔	○	◑	○
IR Radiometry - Air	○	○	○	◑	○	○	○	○	◔	◔	○	◔	◔	○	◑	◔
IR Spectrometry - Land	○	○	○	◔	○	○	○	○	◔	○	○	◔	◔	○	◔	○
IR Spectrometry - Air	○	○	○	◔	○	○	○	○	◔	○	○	◔	◔	○	◔	○
Acoustic - Land	◔	○	◔	◑	◑	◑	◑	◔	◑	○	◑	◑	◑	◔	◑	◔
Acoustic - Air	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
LIDAR - Land	○	○	○	◑	○	○	○	○	◔	○	○	◔	◔	○	◑	○
LIDAR - Air	○	○	◔	◑	○	○	○	○	◔	◔	○	◔	◔	◔	◑	◔
Nuclear Technology - Land (non-metallic only)	◔	○	◑	◕	◑	◑	◔	○	◕	◔	◑	◑	◑	○	◕	◑
Nuclear Technology - Air (non-metallic only)	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Visible Imaging - Land	○	○	○	◔	○	○	○	○	◔	○	○	◔	◔	○	◔	○
Visible Imaging - Air	○	○	○	◔	○	○	○	○	◔	○	○	◔	◔	○	◔	○
MMW Radiometry - Land	○	○	○	◔	○	○	○	○	◔	○	○	○	○	○	◔	○
MMW Radiometry - Air	○	○	○	◔	○	○	○	○	◔	○	○	○	○	○	◔	○

Scale: ○ ◔ ◑ ◕ ●

Poor — Average — Most Applicable

3.8 REFERENCES FOR SECTION 3

1. "The National Atlas of the United States of America", United States Department of the Interior Geological Survey, Washington, D.C., 1970

2. "Physics of the Earth", Frank D. Stacey, John Wiley & Sons, Inc., 1969

3. "Street Atlas USA", Delorme Mapping, Computer Program version 2.0 for Windows, 1993.

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Section 4

SENSOR PRODUCTS

Section 4 provides detailed descriptions of the currently available sensors using the technologies described in Section 2. Each product description describes capabilities, performance parameters, known limitations, company name, and price. As in the Tutorials section (Section 2), the products described herein are divided into two categories: "State-of-the-Art" that refers to technologies currently available off-the-shelf, and "Emerging Technologies" which are promising technologies that exist in the laboratory or are in the field-proving stage and have not yet been commercially deployed.

The information presented in this section has not been verified for its accuracy. The correct procedure would be to obtain each sensor and perform a scientific evaluation and document the results. In the interest of both time and resources we have elected to provide data as obtained from each manufacturer or supplier. The user should consider the performance characteristics presented as representing the manufacturer's or suppliers' perspective. No effort was expended to validate this information or to ensure its accuracy.

Every effort has been made to make this list complete, this section may not include all available sensor products. All known sensor products that we have been able to identify have been included.

4.1. STATE-OF-THE-ART SENSOR TECHNOLOGY PRODUCTS

The term "State-of-the-art" refers to technology solutions that are mature, well-understood, and are available off-the-shelf. The products listed here are organized by technological categories, similar to the organizational content of the Tutorial section (Section 2). Technologies that show promise but are still in the research stage are listed in Section 4.3, "Emerging Technologies."

Information in this section is organized as follows and includes products of the companies listed in the sub-paragraphs:

- 4.1. State-of-the-Art Sensor Technology Products
  - 4.1.1. Magnetometers
    - 4.1.1.1. Proton Precession Magnetometers
      - 4.1.1.1.1. GEM Systems
      - 4.1.1.1.2. Geometrics
      - 4.1.1.1.3. Scintrex
    - 4.1.1.2. Optically Pumped Atomic Magnetometers

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The following sensor technology categories do NOT appear in this section because no vendors that currently offer products suitable for OEW location using this technology have been located:

Fiber-Optic Magnetometer
SQUID Magnetometer
Electron Tunneling Magnetometer
Ultrasonic Sensors
Seismic Imaging Sensors
Infrared Imaging Spectrometry
Nuclear Technology

4.1.1. Magnetometers

4.1.1.1. Proton Precession Magnetometers

For a tutorial on proton precession magnetometers, refer to Section 2.2.1. To view a summary of the magnetometer vendor's capabilities, refer to the Magnetometer Summary Information Table in Section 4.3.1.

4.1.1.1.1. GEM Systems, Inc.

Toronto, Canada
Phone: (905) 764-8008
Key Contact: Ivan Hrvoic

US Representative: Terraplus USA Inc.
625 W. Valley Road
Littleton, CO 80124
Phone: (303) 799-4140
FAX: (303) 799-4776
Key Contact: Jerry McJunkin, President

(GEM also sells a potassium-based optically pumped magnetometer. Refer to Section 4.1.1.2.2.)

Description
GEM sells an Overhauser Effect magnetometer. The Overhauser effect is an enhancement over standard proton precession magnetometers that yields up to ten times the sensitivity. It is said to offer all of the benefits of optically pumped magnetometers (omnidirectional, low power consumption, high sensitivity, portable), but without the cost. The only drawback is that optically pumped magnetometers can sample at up to 20 Hz, whereas the Overhauser units can only sample at a maximum of 5 Hz.

Their GSM-19 is the product name for their omnidirectional sensor with interchangeable configuration. It can be configured either as a conventional proton precession magnetometer, a gradiometer, or as an Overhauser effect magnetometer (and can be upgraded after purchase to save cost). It is a lightweight, man portable unit weighing only 2.1 kg.

These are available as standard "total field" gradiometer, marine (underwater), or airborne configurations. There is also an Omnidirectional very-low-frequency (VLF) option which can sense magnetic fluctuations between 15 and 30 Hz. They retain all data on-board and can be integrated with a global positioning satellite (GPS) receiver for accurate location stamping of findings.

Sensitivity: Proton Precession unit: 0.01 nT
Overhauser effect unit: 0.001 nT

Price: A Total Field System sells for $9K.
Gradiometer configuration: $12.5K

4.1.1.1.2. Geometrics
395 Java Dr.
Box 497
Sunnyvale, CA. 94089
Phone: (408) 734-4616
Fax: (408) 745-6131
Key Contacts: Ross Johnson (sales)
Lynn Edwards & Ken Smith - Tech reps

(Geometrics also makes two optically pumped atomic magnetometers. Refer to Section 4.1.1.2.3.)

Description

Geometrics offers a portable proton precession magnetometer called the G-856AX. It is a self-contained unit with enough memory to hold 12,000 readings for later downloading and analysis. Alternatively, a "real-time" RS-232 option allows measured values to be immediately downloaded to a computer via the serial port.

Salient features:

- Sensitivity to 0.1 gamma
- Weight: 10 lb. (sensor plus console)
- Comes with batteries, staff, chest harness, interpretation manual.

As is standard for all proton magnetometers, it won't operate in fields less than 0.2 Gauss. = 20,000 gammas.

The model 856 is available in gradiometer mode by incorporating a second sensor; resulting in the more precise location of shallow objects. The model 866 combines the magnetometer with a built-in graphic recorder.

Sensitivity	
• Model 856AX	0.1 gamma
• Model 856AGX (Gradiometer config.)	0.03 gamma/foot (3 foot sensor spacing)
Price	
• Model 856 AX	$4,950
• Model 856AGX gradiometer conversion kit	$1,620

4.1.1.1.3. Scintrex

222 Snidercroft Road
Concord, Ontario
Canada, L4K 1B5
Phone: (905) 669-2280
Fax: (905) 669-6403
Key Contact: Richard Lachapelle

(Scintrex also makes a cesium-vapor optically pumped magnetometer developed especially for ordnance detection. Refer to Section 4.1.1.2.5 for more details.)

Description
Scintrex makes a proton-precession "WALKMAG" portable magnetometer and/or gradiometer called ENVIMAG. This instrument features 1/2 second sampling rate, high-capacity memory, graphics display and processing software for the PC.

Sensitivity: 0.1 nT

Price: US $5K including processing software.

4.1.1.2. Optically Pumped Atomic Magnetometers

For a complete description of the operation of these sensitive magnetometers, refer to Tutorial Section 2.2.1.2.

4.1.1.2.1. Australian Defense Industries, Ltd. (ADI)
Fallon Street
Albury, NSW 2640, Australia
Tel: (060) 25 1100
Fax: (060) 40 1990

ADI's US agent is:
Amadeus, Inc.
North Kent Street, Suite 912
Arlington, VA 22209
Tel: (703) 243-6100
FAX: (703) 522-9126
Contact: John Marley, Mark Turner

Geophysical Research Institute
University of New England
Armidale, N.S.W. 2351

Australia
Phone: +621 (067) 73 2617
Fax: (067) 71 1661
Key Contact: Dr. John Stanley

Description
GRI is the research portion of the University of New England (based in Australia). They also have a technology spin-off branch, called Geophysical Technology, which claims to have been in the magnetometer business for more than 20 years. Currently they sell only one product, a high-definition magnetometer system called TM-4 which is used by the Australian Department of Defense.

The TM-4 is a portable unit (can be handheld or vehicle-mounted), capable of recording 400 samples per second. Their sales literature claims it to be not just a magnetometer, "...but a complete data acquisition, processing, interpretation, and documentation system." They also bill it as the "most sensitive and best performing magnetic EOD (electronic ordnance detection) system presently available," although they are comparing it the most popular handheld magnetometers. It is designed to work with optically pumped cesium sensors from Geometrics and Scintrex. GRI has in the past combined two of these for enhanced ground sensing, and four or more ganged together for underwater work.

Other noteworthy developments include:

- Incorporation of differential GPS for centimeter-level accuracy and immunity to foliage interference.

- A digital magnetic compensation system which obviates the need to construct the sensor out of non-magnetic components, and does not require calibration in a magnetically quiet environment.

- A submersible sled has been developed for performing explosive ordnance detection in shallow marine conditions.

- In-house image processing software is able to provide an indication of the depth of the magnetic source. New software containing "enhancement features" are slated to be released soon.

- Computer-aided interpretation tabulates the position, depth, and size of ferrous items requiring investigation.

The system is available in either a handheld or a ground-towed configuration.

Sensitivity: 0.01 nT based on a cesium magnetometer. 0.005 nT based on a helium magnetometer. Both allow up to 400 measurements per second, a relatively high sampling frequency.

Price: US $30K just for the magnetometer; around US $100K for a complete system. ADI has stated that they prefer to sell their EOD scanning services at competitive rates.

4.1.1.2.2. GEM Systems, Inc.

Toronto
Phone: (416) 764-8008
Key Contact: Ivan Hrvoic

US Representative:
Terraplus
625 West Valley Road
Littleton, CO 80124
Phone: (303) 799-4140
Key Contact: Jerry McJunkin

(GEM also sells an enhanced proton-precession magnetometer. Refer to Section 4.1.1.1.1.)

Description
GEM has recently introduced a potassium-based optically pumped magnetometer called the GSMP-20, which was originally prototyped for the US Geological Survey. The unit can be configured as a gradiometer and towed from a helicopter. Its sensitivity is claimed to be 4 to 5 magnitudes better than anything else on the market.

The unit was designed for seismic and oil exploration, and has been used both on the ground and in the air.

Sensitivity (Gradiometer configuration): 0.01 pT (pico-Tesla) for up to 20 Hz sample rate. Resolution of 0.01 nT.

Price: Total-field configuration is $25K
Gradiometer configuration is $45K

4.1.1.2.3. Geometrics
395 Java Dr.
Box 497
Sunnyvale, CA. 94089
Phone: (408) 734-4616
Fax: (408) 745-6131
Key Contacts: Ross Johnson (sales)
Lynn Edwards & Ken Smith - Tech reps

(Geometrics also makes a portable Proton Precession Magnetometer. See Section 4.1.1.1.2.)

Description
EG&G Geometrics markets two optically pumped atomic magnetometers: one employing Cesium, the other Helium. The Cesium magnetometer is the model 822, a digital version of what is popularly known by the Navy as the Mk22. A next-generation Mk22, called the 858, is being planned and will incorporate a data logger and a GPS receiver to speed surveys and make them more accurate. The 858 will eventually replace the 822 after its introduction in December, 1994. The helium version is called the model 833.

Both current products share similar characteristics. Both are packaged as a 2 cylinder pair with a cable between them; each tube being approx. 7" by 3" OD. A separate electronics canister is longer; about 14" by 2.5" OD. Both have "dead zones" (30-degree directions in which they are not sensitive); the Cesium version has two 30-degree equatorial and two 30-degree polar dead zones, which leaves an active area of 60 degrees in each direction. Helium has no polar dead zone, but its equatorial dead zone is "a little wider." Both the Helium and Cesium instruments generate a small amount of RF leakage.

Both sensors also require an external counter to convert the Larmor frequencies into an RS-232 signal that represents the oscillation measurements as a gamma reading. The Cesium magnetometer comes with a counter that has a resolution of 0.1 gamma with a sampling rate of 10 Hz. The Helium magnetometer does not come with its own counter; a matched counter that is capable of resolving 0.01 gamma with a sampling rate of 100 Hz must be purchased separately.

Sensitivity
Cesium: 0.01 nT at 0.1 nT resolution
(0.01 nT for the airborne version)
Helium: 0.01 nT at 0.01 nT resolution

Prices
- Cesium model 822A (for Airborne unit without counter) or model 822L (for a land unit with counter) is $14.5K
- Helium model 833 (Airborne without counter) sells for $17.5K.

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- High-performance counter as described above sells for $15.8K. (Alternatively, a third party sells similar high-performance counter boards which mount into a PC and can measure up to 16 channels simultaneously for only $6K. Contact Guide Technology, Inc. in San Jose, CA (408) 246-9905.)
- The 858 next-generation product (slated for introduction before December '94) will sell for $14.5K. Upgrade kits to turn an 822 into an 858 are available for $5K.

4.1.1.2.4. Geonex Aerodat

3883 Nashua Drive
Mississauga
Ontario, Canada L4V 1R3
Phone: (905) 671-2446
Fax: (905) 671-8160
Key Contact: Mr. Doug Pitcher

Description
Geonex Aerodat is a full-service airborne sensor company; they not only manufacture their own sensors and post-processing software, but they will also perform the site survey. They specialize in helicopter and fixed wing geophysics. Although most of their airborne surveys are for the oil and mining industries, they do have two sensor types that are ideal for detecting buried ordnance: a combination of an EM magnetometer and a gradiometer. (See Section 4.1.2.1 for a more detailed description of their EM sensor.) Aerodat uses two Scintrex split-beam optically pumped cesium magnetometers coupled to a digital signal processor designed by Aerodat.

This sensor combination is called a "towed-bird" gradiometer designed to be towed behind a helicopter. By combining the two sensors and using processing software, both magnetic fields and conductivity can be remotely measured. They also can configure a 2-axis gradiometer, comprised of four aligned sensors which yields both a vertical and horizontal gradient.

Sensitivity:
<u>Airborne Optically Pumped Cesium Magnetometer</u>
- 0.1 sec sampling time
- Sensitivity 0.05 nT

<u>Vertical Gradiometer Configuration</u>
- Two high-sensitivity magnetometers rigidly mounted and separated by a vertical distance of 3.0 meters.
- Sensitivity to 0.01 nT/m (down to 0.001 nT/m in the lab)

Price: Aerodat only sells their surveying services; their sensor equipment is not for sale. Typical survey costs break down as follows: $5K for the helicopter, $5K for their equipment, $2K per day to actually conduct the survey. They can typically cover 100 acres per day. (When pressed, however, a ballpark figure for a towed-bird sensor system, which includes the bird, recording devices, instruments, rack-mount computer for real-time processing, GPS integration, and "spares" was unofficially quoted at about $500K.

4.1.1.2.5. Scintrex

222 Snidercroft Road
Concord, Ontario
Canada, L4K 1B5
Phone: (905) 669-2280
Fax: (905) 669-6403
Key Contact: Richard Lachapelle

Description
Scintrex makes two classes of portable, handheld magnetometers. The first, called the "SMARTMAG," is a cesium-based optically pumped magnetometer developed especially for ordnance detection. (The second is a proton-based magnetometer discussed in Section 4.1.1.1.3.) Optional items are on-board memory and mapping software.

Sensitivity: 0.01 nT, at a 10 Hz sampling rate.

Price: The SMARTMAG sells for between US $13K - $18K, depending on options.

4.1.1.2.6. Varian Associates

3100 Hansen Way
Palo Alto, CA 94304
Phone: (415) 493 4000

Description
Varian used to make the Varian V92, a handheld analog magnetometer known to the Navy as the Mk22. The product line was sold off, and is now manufactured by Scintrex in Canada and Geometrics in the US. Refer to Sections 4.1.1.1.3 and 4.1.1.1.2, respectively, for more information on these companies.

A digital display is provided with a resolution of 1 nT. Audio is fed to operator; if the operator can discern 15-20 Hz then the claimed 1 nT sensitivity can be achieved.

4.1.1.3. Fluxgate Magnetometers

For a complete description of the theory and operation of fluxgate magnetometers, refer to Tutorial Section 2.2.1.3.

4.1.1.3.1. Applied Physics Systems (APS)

897 Independence Ave. Suite 1C
Mountain View, CA 94043
Phone: (415) 965-0500
Fax: (415) 965-0404
Key Contact: Bob Goodman

(APS also makes SQUID magnetometers and miniature 3-axis fluxgate magnetometers that can be incorporated into systems that require magnetic field measurement. Refer to Sections 4.2.1.2.2 and 4.2.1.3.1 for more information on these products.)

Description
Applied Physics Systems makes a variety of fluxgate magnetometers. Their APS428C single-axis magnetometer was designed for use either as a conventional magnetometer or as a clamp-on DC milliammeter (for measuring small current flow through wires).

Their model APS520/520A is a sensitive 3-axis fluxgate magnetometer for benchtop use. With its miniature probe (1" x 1" x 2.5"), the system can be used to measure small magnetic fields in confined spaces.

Sensitivity: The range for both the single-axis and 3-axis systems is 1 μGauss to 2 Gauss; (same sensor used in both systems.) Noise is quoted at 3×10^{-7} Gauss rms/$\sqrt{\text{Hz}}$

Price: A complete single-axis system sells for $3K; 3-axis systems range from $5K to $7K.

4.1.1.3.2. Bison Instruments
5708 W. 36th Street
St. Louis Park, Minnesota 55416
Phone: (612) 926-1846
Key Contact: Bret Smith

Description
Bison resells basic, no-frills 1-button magnetometers from Russia. Their magnetometers are designed to measure Earth's magnetic field intensity to a resolution of only 2 gamma, which makes them ideal for detecting buried drums, large ore bodies, or any other large ferrous mass. The company's primary business is the manufacture of shallow- to medium-depth seismic exploration systems.

Sensitivity: 2 nT

Price: $1500.

4.1.1.3.3. Foerster Instruments Inc.
140 Industry Drive.
RIDC Park West
Pittsburgh, PA 15275
Phone: (412) 788-8976
FAX: (412) 788-8984
Key Contact: Cheryl Hodnicki, Tim Brown

Description
Foerster is a German firm that specializes in desktop magnetometers for the inspection of small parts during manufacturing. They are also well-known for their FEREX 4.021 handheld analog magnetometer, popularly known as the "Mark 26."

The FEREX 4.021 locator consists of a pair of fluxgate type sensors mounted 400 mm apart, in-line When operated vertically, it measures the difference in the vertical component of the magnetic field between the sensors. For source depths greater than about 2m, this difference approximates the vertical gradient of the vertical component of the anomaly. A switch enables a sensitivity to be selected from a range between 3 nT and 10,000 nT. The choice of sensitivity setting that can be used is determined by the amplitude of the noise envelope in the search area.

The magnetometer, which is specifically designed for the detection of OEW in the ground, provides operator feedback via an audio tone and an analog meter. The unit is also rated for underwater detection for depths of up to 100 m.

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Foerster also offers an enhanced package that consists of the FEREX locator coupled with a data storage system and a special PC evaluation program. It is used for logging of the data in real time; it encodes positional information by dead reckoning.

Other man-portable units designed for mine detection include the MINEX 2FD and the older METEX 4.125, which can penetrate ground to a depth of 1 meter.

Sensitivity: Sensitivity in nT was not offered, but they did claim to be able to sense a 8.8 cm tank shell at a depth of 3 m.

Price: The complete FEREX 4.021 system, including control unit, probe, power supply, and headphones, is $17.4K.

4.1.1.3.4. GEO-CENTERS, Inc.
7 Wells Avenue
Newton Centre, MA 02159
Phone: (617) 964-7070
FAX: (617) 527-7592
Contact: Richard Russell

Description
GEO-CENTERS, Inc. is a company that specializes in buried unexploded ordnance detection, location, remediation, and quality assurance as well as computer-based non-intrusive site characterization. They have developed and commercially deployed a sensor ideally suited for buried OEW detection called STOLS® (Surface Towed Ordnance Locator System). It consists of a towed array of 7 full-field cesium-vapor magnetometers (similar to those employed in the Navy Mk22 ordnance locator) coupled to a differential Global Positioning System (GPS) with data acquisition hardware and software. Custom postprocessing software locates and characterizes detected magnetic anomalies. Site image maps are provided minutes after data transfer (which can be accomplished anytime during or after a field exercise). Target analysis takes place at a rate of approximately 150 targets/hour, yielding next-day availability of target reports.

Survey productivity of 25 to 30 acres per day has been achieved in open areas of gently rolling topography, where vehicular speeds averaged 8 to 10 miles per hour.

An operator portable adjunct is also available for fielding either separately for small sites or in combination with a vehicular survey to cover areas which are not traversable by the vehicular system.

Each STOLS® magnetometer has a sensitivity of 0.1 gamma. They have studied airborne use of STOLS® and concluded that it was possible; however, as of publication date it had never been tried. They would be willing to work with an outside sponsor to develop this airborne system.

The proprietary analysis software runs on a Silicon Graphics Indigo workstation under Motif (although the data gathering program runs on a PC under Microsoft Windows). It is able to determine the absolute position (latitude, longitude), depth, magnitude of dipole, and infer the object's identity based upon the magnetic signature.

Sensitivity: Each magnetometer has a 0.1 gamma sensitivity at 0.5 nT resolution

Price: STOLS® is available as an ordnance detection and a geophysical characterization service. Prices vary depending on site conditions; at sites where 8 to 10 miles/hour coverage can be achieved, the price is approx. $1,000/acre.

4.1.1.3.5. Sage Earth Science (EG&G Idaho)
2300 N. Yellowstone
Suite 206
Idaho Falls, ID 83401
(208) 522-5049
Key Contacts Nick Josten
Glen Carpenter (208) 526-4166

Description
Nick Josten is a user of ground sensors for subsurface environmental location problems (buried tanks, pipelines, solid waste, etc.). He complained that no commercial magnetometer available could scan large acreages in a reasonable amount of time, so he constructed his own, called the Rapid Geophysical Surveyor, and is starting a new company to commercialize the development.

In his words, the most important characteristic of a magnetometer is spatial resolution; the distance between successive samples while traveling. This, in his mind, is even more important than resolution or sensitivity. (For example, a sensitivity of 0.01 nT is overkill for a ground-towed system which detects ordnance producing a magnetic field strength of 0.2 Teslas.)

So Mr. Josten, along with Glen Carpenter, constructed their own wheelbarrow-type gradiometer consisting of a pair of fluxgate magnetometers that could take measurements 100 times a second. The unit can be pushed by a single human and allows them to walk faster than other units would permit. The wheel is optically encoded for dead-reckoning position establishment.

In their view, the unit is useful, little processing is necessary, and all magnetometers in the future will be built this way. Currently there's only one working system available for hire; and they will build others to suit.

Sensitivity: the magnetometers they've incorporated are 0.1 nT/m; data collection rate: 100 Hz at walking speeds.

Price: Unknown; their estimate would be around $5K.

4.1.1.3.6. Schonstedt Instrument Company
1775 Wiehle Avenue
Reston, Virginia 22092-5199
Phone: (703) 471-1050
FAX: (703) 471-1795
Key Contact: O.K. Davis

Description
Schonstedt makes three similar handheld magnetometers (which they call "locators") designed for near-surface pipe and well casing location, although they also proudly point out that many of their previous products can be found on the moon and "on every satellite." All of their gradiometers (which they term "magnetic locators") are similar in construction and usage: they are handheld, portable units located on top of a 30-inch probe in which are contained two fluxgate magnetometers, spaced 14 inches apart.

Absolutely none of their literature specifies sensitivity ratings, and a follow-up phone call reveals that they've never collected this information. Below is a summary of their product line:

MAC-51B is a magnetic and cable locator. When used in conjunction with a miniature pipe-insertable transmitter, it can also locate plastic pipes and information cables (the cables act as a radiating antenna to the transmitter).

Model GA-52C is a fluxgate handheld magnetometer for buried ferrous metal (iron, steel) detection. It does not respond to buried aluminum, copper, etc.

The model GA-72CV was created specifically for ordnance and weapons detection; many have been used in Saudi Arabia. Although sensitivity specifications weren't given, they measure product effectiveness by sentences like, "It'll find a septic tank cover/handle up to 4 ft. deep; a manhole cover at 8 ft. depth; 175 mm projectile up to 5 ft. deep; 81 mm mortar up to 1 ft. depth, an MK-81 up to 9 ft. deep; and a discarded handgun up to 1 ft. depth." The 2.5 lb., handheld unit runs for 30 hours on 4 AA batteries.

They only sell their products through distributors.

Specifications: The instrument is still being benchmarked, but the sensitivity is believed to be in the range of 0.5 and 0.1 Gamma.

Prices

MAC-51B	$1,825.00
GA-52C	815.00
GA-72CV	850.00

4.1.2. Electromagnetic Induction

For a complete description of electromagnetic induction sensors, refer to the tutorials in Sections 2.1.2, 2.2.2, and 2.3.2. To view a summary of the EM induction vendor's capabilities, refer to the EM Induction Summary Information Table in Section 4.3.2.

4.1.2.1. Geonex Aerodat

3883 Nashua Drive
Mississauga
Ontario, Canada L4V 1R3
Phone: (905) 671-2446
Fax: (905) 671-8160
Key Contacts: Mr. Doug Pitcher
Mario Steiner, President
Jeff Gamey, Physicist

Description
Aerodat has designed and manufactured a helicopter-borne, multi-frequency electromagnetic system consisting of two or three coaxial coil pairs operating at approximately 935, 4600, and 66,000 Hz, and two or three horizontal coplanar coil pairs operating at 500, 4275, and 33,000 Hz. The coils are mounted in a Kevlar "bird" at a separation of approximately 7 meters. The system measures in-phase and quadrature responses at each frequency with a 0.1 second time constant. Aerodat operates 4, 5, and 6 frequency systems and the selection of the most appropriate system can be made for each specific application.

This system is ideal for providing detailed structural and geometrical information as well as excellent horizontal mapping techniques. Structural detail is provided by the vertical coil pairs and geometric information is provided by the combination of the coplanar coil pair responses versus the coaxial coil pair responses. The horizontal mapping capability is provided by the multiple horizontal coplanar coil pairs.

This Aerodat system generates resistivity maps (which can be converted into conductance maps, since one is the reciprocal of the other) over the terrain measured. From this map, clusters of buried metallic ordnance could be identified due to the local reduction of conductance values in those areas. However, the spatial resolution is inadequate to identify small individual buried ordnance. The lack of depth resolution also makes it ambiguous to find the depth of buried ordnance.

They also make radiometric sensors for detecting nuclear substances, and very low frequency EM sensors for detecting "long conductors."

Sensitivity: They quote a sensitivity of 1 ppm or less, which translates to -60 dB.

Prices: Aerodat only sells their surveying services; their sensor equipment is not for sale. Typical survey costs break down as follows: $5K for the helicopter, $5K for their equipment, $2K per day to actually conduct the survey. They can typically cover 100 acres per day.

4.1.2.2. Geonics Ltd.

1745 Meyerside Drive Unit 8
Mississauga, Ontario, Canada L5T 1C6
Phone: (905) 670-9580
Fax: (905) 670-9580
Key Contacts: Miro Bosna, Mike Catalano

Description

Geonics manufactures three units that can be used for buried ordnance detection.

Their EM61 is a portable electromagnetic induction sensor which can be pulled around as a trailer or carried with a shoulder harness. (An odometer mounted on the trailer axle records the distance traveled.) Two receiver coils are employed, each 1 x 1m square and spaced 40 cm apart. A handheld data logger is used to view and log the data. According to Simon Boniwell, the company's contact, the advantages include "superior resolution and noise rejection and data processing which allows suppression of near-surface 'noise' and the calculation of apparent depth to the target".

Their EM38 ground conductivity meter is one meter long and can detect both ferrous and non-ferrous metal by measuring the in-phase and quad phase components of the response. The instrument, operating at 14.6 kHz, is 'walked' around the survey area with an optional data logger. As compared to the EM31 (below), the EM38 is optimum for the detection of small targets near the surface.

The EM31 ground conductivity meter is a larger version of the EM38, 4 meters long and a correspondingly greater depth of exploration. The system operates at 9.8 kHz and is also 'walked' around the survey area with an optional data logger.

Under most conditions, the EM61 would be considered the best choice of these instruments.

The company also offers GEOSOFT software for turning raw data into "...attractive, meaningful colored and shaded-relief maps."

Sensitivity:
EM61: 8 nV/m^2 sensitivity, 16 nV/m^2 resolution
EM38: 3 x 10^{-5} γ for both sensitivity and resolution.
EM31: 5 x 10^{-5} γ for both sensitivity and resolution.

Price
EM61: $12K; for trailer mount add $2.1K
EM38: $7K; for data logger add $3.8K
EM31: $14K; for data logger add $3.8K.

Units are also available for rental.

4.1.2.3. Pylon Electronics Inc.

US Representative: NAECO Associates, Inc.
1925 North Lynn Street, Suite 900
Arlington, VA 22209
Phone (703) 524-4551
Fax (703) 525-4286
Key Contact: E. Stack Gately
For sensitivity, talk to John Elliott at Pylon, Ottawa (613) 226-7920

Description
Pylon makes the Vehicle-mounted Ordnance Detector (VMOD) system which operates as a pulse-induction detector similar to a proton precession magnetometer. It was originally designed for quality control for Level II range clearing assignments (clearance to a depth of 2 feet below the surface).

The technical highlights of this system include: towed over ground, real-time detection, ferrous & non-ferrous metal detectability, audible & visible alarms, detections logged in computer, and interface to global positioning satellite (GPS) receiver.

The vehicle requires two people to operate and is able to move at a speed of 10 kilometers per hour. It can cover an area of 3.3 acres per hour. This system has been tried with the U.S. Navy at 29 Palms, CA and with the Canadian Armed Forces at the CFB Chilliwack, B.C., and CFB Calgary, Alberta. It is being improved for depth determination and object classification capabilities. A hand-held version is also being developed.

Sensitivity: Dr. Elliot of Pylon Electronics revealed that no sensitivity readings had been taken, but could quote various object sizes at various depths which made it impossible to compare.

Price: $63K

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4.1.3. Ground-Penetrating Radar

This section describes in detail vendors who sell a radar-type sensor that could potentially be used to detect buried OEW. "Land-based" means it can be used in close proximity to the ground, typically mounted in a vehicle.

To view a summary of the GPR vendor's capabilities, refer to the GPR Summary Information table in Section 4.3.3

4.1.3.1 Land-based

The term "land-based" means it can be used in close proximity to the ground, typically mounted in a vehicle. They are typically operated at a distance within a tenth of a wavelength of the ground in order to minimize surface reflections and to maximize the transfer of energy into the ground.

4.1.3.1.1. American Underwater Search and Survey, Ltd.

Box 768
Cataumet, MA 02534
Phone: (508) 564-6500
Fax: (508) 564-6600
Key Contact: John Fish

Description
AUS&S uses side-scan radar to image objects in bodies of water, particularly mines. Mr. Fish, the company's representative, claimed the technology could also effectively identify objects on the bottom of lake beds.

4.1.3.1.2. CRREL

US Army Corps of Engineers
Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, NH 03755
(603) 646-4100
Key Contacts: Austin Kovacs x4411
Steve Arconne x4368
Burt Yankielun

Description
CRREL, being a research lab, doesn't produce or provide equipment. Their main areas of expertise are FM-CW radar, low frequency/high power antennas, signal processing, subsurface radar patterns, and antenna "directivity." They have used an FM-CW radar at microwave and millimeter wave frequencies to measure ice

thickness. They have also successfully surveyed the bottoms of lakes and rivers; they can see up to 30m in depth. In shallow water (of about 5 m), you can penetrate 6-10m deep in sediment.

They've had some FM-CW successes in their research using the millimeter wave band, on both airborne and ground platforms, but their eventual goals of increased SNR and resolution have not yet been attained.

Sensitivity and Price: Information not provided.

4.1.3.1.3. Geophysical Survey Systems Inc. (GSSI)

Box 97
13 Klein Dr.
Salem, NH 03073-0097
Phone: (603) 893-1109
Key Contact: Dan Delea, Alan Schutz

Description
GSSI sells modular ground-operated GPR components that allow you to mix-and-match the antenna and the processing box to meet the application. They claim to have been in the GPR hardware business the longest (25 years) and to have sold more equipment than anyone else. (They appear to be a major player by their competitors; GSSI's name came up frequently during phone conversations.) Their selection of antennas ranges from 2.5 GHz to 20 MHz in center frequency.

Three signal processing boxes (to which you hook up the antennas) are offered. All of them will accept the full range of antennas offered. The three systems are:

SIR3 is single-channel analog system

SIR10 is a multi-channel digital system; all software controlled. The standard configuration is two hardware input channels for two antennas. The unit can accept up to four antennas; alternatively you can soft-configure four channels to multiplex different measurements from a single input antenna.

SIR2 is a scaled-down version of SIR10, allowing for a maximum of 2 channels.

Dan Delea, GSSI's sales rep, claimed that their pulsed, time-domain products could operate at higher frequencies and up to eight times faster than their competitors (most of which offered FM-CW GPR), and that their equipment has been used to locate buried ordnance using the 500 MHz band.

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Sensitivity: SNR of the SIR 10 and SIR 2 was quoted at 160 dB. Pulse widths range from 0.1 to 12 ns.

Prices

SIR3:	$17.9K, not including antenna.
SIR10A:	$40K
SIR2:	[TBD, but probably $19-20K.]

Antenna Prices:

High-frequency horns:	$14K per pair;
Low-freq. bistatic pair:	$12K
Others:	about $4.3K - $4.8K

4.1.3.1.4. GeoRadar, Inc.

19623 Via Escuela Drive
Saratoga, CA 95070
Phone: (408) 867-3792
Key Contact: Doug Crice
Mike Bashforth (805) 688-1745.

Description

GeoRadar produces what their representative claims is "...the only commercial FM-CW GPR in the world." The ground-towed product is based on a unit developed for the Navy to aid in UXO location, and the technology was recently transferred to commercial industry.

Their GPR technology is FM-CW. The claimed benefits of which are accurate images of subsurface objects, less backscatter from extraneous objects, better signal-to-noise ratio, and less interpretive and operative training necessary. In use, data is viewed on the large LCD display as it is acquired, and stored on a floppy for later post-processing on a PC.

Currently a demo unit is functional. A shippable product should be ready by October of 1994. (Quoted Sept. 22, 1994).

Specifications:
Operating Frequency: 100 MHz - 1 GHz
Dynamic Range: 96 dB
Range Resolution: 15 cm
Unambiguous Range 10 meters

Price: $25K

4.1.3.1.5. Geoscience

ABEM Geoscience
Skolgatan 11
Malå
S-930 70 Sweden
Phone: +46 953 10074
Fax: +46 953 10225
Key Contact: Olof Forslund (Director of company)

Description

ABEM Geoscience makes the RAMAC borehole radar system, claimed to be the only commercially available borehole system in the world. Originally developed for the nuclear power industry, their sensor is now finding uses worldwide, essentially for underground tunnel investigations and for detecting underground cracks in rock.

The sensor is comprised of a long tube containing the transmitter and receiver at opposite ends. A bore hole is made in the ground and the sensor lowered into it slowly. Measurements are taken at regular distance intervals as the probe is lowered into the ground. (Each reading takes about 10 seconds.) Optical fibers are used for transmission of the trigger signals from the computer to the borehole probe.

The unit employs frequencies in the 10 to 100 MHz range which the company claims is ideal for normal radar-absorbing bedrock. They claim this system can detect cracks up to 100 meters from the borehole.

The company will also be releasing a GPR this summer, said to be lightweight and completely digital. Frequency range will be from 50 to 400 MHz.

Sensitivity: Numbers provided are difficult to compare. The receiver's bandwidth is 10 to 200 MHz, but no sensitivity is offered. "The least significant bit at the antenna terminals is 1 μV."

Price: The RAMAC borehole radar sells for between US $120K - $250K, depending on winch size and software package(s). The GPR is planned to sell at between US $35K and $40K.

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4.1.3.1.6 Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94551
Phone: (510) 422-1100
Key Contact: Paul Sargis, David Fields

Description
LLNL's standoff, side-looking, ground-penetrating impulse radar system has been used to detect buried mines and other miscellaneous buried objects. In its present configuration, the system covers 400 MHz to 1500 MHz with a pulse power of 300 kW. Data acquisition hardware and a SAR processing workstation are mounted inside a panel truck, while the antennas are mounted on the truck's roof at an elevation of four meters. The system can cover two acres per hour. It will eventually be adapted to operate from an airborne platform.

Sensitivity: Metal mines buried in natural desert vegetation have been imaged with signal-to-clutter ratios typically on the order of 6:1. Metal disks have been detected to a depth of 40 cm. Range resolution and cross-range resolution are approximately 25 cm.

Price: This system is still under development. Companies may pursue a cooperative research and development agreement (CRADA) with LLNL.

(Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48)

4.1.3.1.7. Penetrator

Niagara Falls, NY
Phone: (716) 731-4369
Key Contact: Tony Alongi

Description
Penetrator makes a ground-towed GPR designed for highway condition assessment, but it has also been successfully applied to buried mine detection. Their typical penetration depth is one to three feet.

They feel their unique capabilities lie in their techniques to eliminate surface echoes. Their radar also has a narrow beam and has small antenna side-lobes, which minimize external clutter. The sampling rate is high enough to allow a towing speed of 25 mph.

Sensitivity: Signal-to-noise ratio wasn't provided, but they did quote a spatial resolution of 1-3 inches when sensor was less than 1m from the ground.

Price: $60-70K for the sensors; a complete 3-radar system (geared for highway applications) from $100-200K

4.1.3.1.8. Pulse Radars, Inc.

10665 Richmond Suite 170
Houston, TX 77042
(713) 977-0557
(800) 551-9173
Key Contact: Dr. C.T. Wells, President.

Description
PRI makes a vehicle-towed GPR designed for road bed thickness measurements. They were recently awarded an SBIR with the Corps of Engineers for phase I of a system to detect mines. The system is being developed in conjunction with an EG&G division in Albuquerque. NM.

Their standard GPR product resides in a vehicle traveling at highway speeds and shows what's beneath the road in real time. Like many manufacturers, no direct sensitivity ratings are offered. Instead, we get, "A one-ns radar pulse penetrates to 30 inch depths with a resolution of one to two inches. A two-ns pulse could go as deep as five to six feet with lower resolution." A current SBIR they're working on has them employing 3 ns pulses to reach a depth of 20'; this will detect "a large object". 4 ns pulses are ideal for detecting road delamination a few inches below the surface. Their data sheet specifies a receiver output bandwidth of 3 kHz.

Specifications - No comparable sensitivity measurements offered.

Price A self-contained unit costs $75-80K including software. No skilled operator is necessary to run it.

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4.1.3.1.9. Sensors and Software, Inc.

5566 Tomken Road
Mississauga, Ontario
Canada L4W 1P4
(905) 624-8909
Key Contact: Dr. Peter Annan - President
Mr. Steve Cosway - General Manager

Description
Sensors and Software Inc. manufactures two portable GPR systems: the pulseEKKO IV and the pulseEKKO 1000. The former is designed primarily for geological mapping and deep sounding applications. The latter is aimed at shallow applications such as pipes, utilities, archaeology, and non-destructive testing.

The pulseEKKO IV systems provides center frequencies from 12.5 MHz to 200 MHz in steps of 2. With the pulseEKKO IV, depths of exploration in excess of 100 meters have been reported in highly resistive terrain such as granites and ice. In coarse grain materials, water saturated or dry, depths of exploration are typically in excess of 30 meters. In clays and slits depths of exploration are usually limited to 1 to 4 meters depending on the pore water conductivity.

The pulseEKKO 1000 operates with antennas at center frequencies between 200 and 1000 MHz. This system has higher resolution than the pulseEKKO IV system and is designed for shallower exploration applications.

Both GPR systems are battery powered and designed to be man-portable. The primary mode of operation is to acquire data and display it in the field as well as record it for post survey processing. Data processing can be done on any PC or workstation. Data processing can be handled by available software from the vendor or can also be processed using a wide variety of available programs for handling seismic and GPR data.

Both systems are optimized for the street step mode or continuous profiling traversing on the ground. The systems are not optimized for flying.

Sensitivity: EKKO IV: 155 dB sensitivity
Pulse width varies from 32-2048 ns

EKKO 1000: 133 dB sensitivity
Pulse width varies from 10-250 ns

Prices: Both pulseEKKO systems sell for $32K USD (complete systems). Extra antennas, untethering electronics, and advanced software are also available.

4.1.3.2 Airborne

4.1.3.2.1. Airborne Environmental Surveys
A division of ERA Helicopter, Inc.
3130 Skyway Drive, Suite 108
Santa Maria, California 93455
Phone: (805) 922-1424
Fax: (805) 922-9152
Key Contact: Robert M. Cameron

Description
AES offers two frequency-modulated, continuous-wave (FM-CW) GPRs intended for helicopter use. The difference between FM-CW over more conventional impulse radar is that you can maximize the time-bandwidth product - essentially putting more power into the pulse. The advantages are higher resolution and, in some cases, better depth penetration (they can penetrate up to 20 m in dry sand).

The units are designed to be flown 150-300 ft. above ground level. AES uses two circularly-polarized antennas to probe vertically at frequencies of 250 to 750 MHz. Primary applications have focused on the detection of man-made objects in landfills, hazardous waste sites, and subsurface plumes of refined hydrocarbons. Like most other GPR manufacturers, their post-processing software is proprietary.

The Department of Energy, after evaluating several GPRs from other manufacturers, rated the FM-CW units from AES the highest. They have just recently developed SAR post-processing techniques that enhance their proprietary GPR hardware. The key contact, Robert Cameron, claimed the enhancement was only useful for trying to pattern subsurface events (for example, for finding land mine patterns).

Specifications:
EMS-20: Pulse Length - 5 nanoseconds
Effective System Gain: > 160 dB

EMS-5: Pulse Length: 500 picoseconds
System Gain: (not listed)

Price: Unlike most other manufacturers, AES will not sell their instruments to anyone; they prefer to be hired to do the site survey, thereby insuring that the instruments are being used and interpreted properly. Large-scale surveys cost about $50 to $60K per day to survey up to 200 acres. A lower-resolution (+/- 50 feet), quick look "reconnaissance" survey is also available.

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4.1.3.2.2. ERIM
Environmental Research Institute of Michigan

PO Box 134001
Ann Arbor, MI 48113-4001
Phone: (313) 994-1200
FAX: (313) 994-4630
Key Contact: David Spector

(ERIM also has done work in multi-spectral imaging. Refer to Section 4.1.5.1 for more details.)

Description
ERIM has produced two technologies of interest: a ground-penetrating SAR, and multi-spectral imaging. They also have GIS system capabilities that allow field workers to radio their magnetometer data to a central GIS computer as it's collected.

Their GPR was designed to detect buried mines, a field they've been dealing with for 20 years. Their system is called RAIL-SAR, and is designed to emulate an airborne SAR for experimental system. Its 100-200 MHz frequency band penetrates both foliage and ground. It can image 2 buried barrels under 1 m of soil; it can also detect disturbed soil.

A new GPR upgrade called the P-3 is also currently being developed by ERIM under ARPA sponsorship. The upgrade will include a UHF channel with an average power of over 300 W that promises to achieve 0.5x0.5 m resolution. The upgrade was expected to be completed before the end of fiscal year 1995.

4.1.3.2.3. Jet Propulsion Laboratory (JPL)

4800 Oak Grove Dr.
Pasadena, CA 91109
Phone: (818) 354-4321
Key Contact: Walt Brawn x4-2110

Description
JPL has developed a multi-frequency, multi-polarization SAR which operates from a NASA DC-8 aircraft. Three frequency bands (UHF-band, L-band, and C-band) are available with center frequencies operating at 439 MHz, 1.25 GHz, and 5.3 GHz, respectively. Each band allows for transmission and reception in either horizontal or vertical polarization. This permits the multi-polarization recording of HH, HV, VH, and VV, which makes it easier to detect underground items. Each band also operates with a bandwidth of 38 MHz and gives a range and azimuth

resolution of approximately 4 meters by 4 meters. The sensor allows look angles from 30 to 70 degrees. The swath width is approximately 3.5 km.

Three frequencies chosen all penetrate the ground at different depths, which can be an advantage when trying to reduce the effects of surface clutter. The 5.3 GHz frequency for example can only penetrate to a depth of a few centimeters, whereas the 439 MHz frequency can penetrate up to 3-4 m in dry soil. If a scan using both frequencies produces a common dark spot, it can be concluded that the object being detected is on the surface. If a dark spot appears only on the 439 MHz image, however, then the object is "deep." This makes it possible to automatically filter out all the surface objects and see only those buried to the low-frequency penetration depth.

Sensitivity: Walt employs a "sigma zero" metric, which will differ for each frequency and look angle. The range is -30 to -50 dB.

Price: Not Available, but the unit and its airplane can be scheduled through NASA.

4.1.3.2.4. Stanford Research Institute (SRI) International
Geoscience and Engineering Center
333 Ravenswood Avenue
Menlo Park, CA 94025-3493
Key Contact: Roger S. Vickers
Phone (415) 326-6200
Fax (415) 859-4325

(SRI also makes an UWB radar. See Section 4.1.3.2.5 for more details.)

Description
SRI does not sell sensing instruments. They develop their own models and perform site surveys only. If they feel the demand is large enough, a sensor will be transferred to commercial industry. SRI has conducted numerous airborne GPR site surveys throughout the United States.

Four GPR families are currently employed: ground-towed, vehicle-mounted, helicopter-mounted, and fixed-wing mounted. (There also used to be a sled-mounted sensor that was successfully used for 20 years; this is no longer in use.)

The vehicle-mounted GPR can fit in a van or on a trailer, and is designed primarily for OEW and mine field detection. The helicopter-mounted system comes in two types: vertical profiling and side-looking synthetic-aperture radar (SAR). Like any other SAR, the post-processing routines are the most critical to effective results, and here too SRI claims to have in-house routines that produce excellent results.

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The high altitude and high resolution of the SAR system enables the rapid coverage a large site and the identification of approximate locations of buried objects. The high resolution of the SAR also enables the overlapping of the SAR images with photographic images to map out the surface objects. Once buried sites are identified, a helicopter-borne vertical-profiling GPR system could be flown over the site for a detailed depth scan. Since the helicopter could be flown at a much lower altitude, vertical profile of the buried site could be obtained.

Mr. Vickers seemed rather proud of their fixed-wing systems, named "Full-Pen 1" and "Full-Pen 2" (short for Full Penetration). This system gives a typical penetration depth of 2 meters, which is enough for them to have detected SCUD missiles, buried tunnels, pipes, and cables in the past. This is the only sensor type on which he would quote sensitivity figures: -40 dB/m^2 (also called -40 "sigma zero"). The other sensors are usually classified by their dynamic range, or the ratio of ground signal return to the signal from the smallest detectable element -60 dB is a reasonable figure.

Sensitivity: The Full-Pen 1 and Full-Pen 2 have a sensitivity of -40 dB/m^2. No resolution figures were provided.

Price: SRI only sells their surveying services.

(SRI also makes a "ground profiler" radar, which is a 1-dimensional downward-looking radar with no 2-D imaging capability. It is not considered a SAR.)

4.1.3.2.5. Stanford Research Institute (SRI) International
Geoscience and Engineering Center
333 Ravenswood Avenue
Menlo Park, CA 94025-3493
Key Contact: Roger S. Vickers
Phone (415) 326-6200
Fax (415) 859-4325

(SRI also makes an airborne synthetic aperture radar (SAR) GPR. Refer to Section 4.1.3.2.4. for more details.)

Description
SRI's ultrawide-band radar (UWB) has been used primarily for foliage penetration, although it has occasionally been used to detect mines and other OEW. It has been deployed on three different platforms: ground-towed at a vertical distance of 12 feet, helicopter-borne at a vertical distance of 50 feet, and fixed-wing at a distance of between 2,000 and 10,000 feet.

All but their helicopter version can perform imaging; this capability was scheduled to be added to the helicopter version by the Summer of '94.

Sensitivity: The UWB radar has a pulse width of 5 ns and a bandwidth of 200 MHz. The corresponding maximum range resolution is 0.75 meter. Resolution: 9 inch resolution in vehicle-borne unit, 3-4 inches vertical resolution in airborne vertical profiling mode.

Price: The units are not commercially available, but could go for approximately $60-70K in small quantities.

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4.1.4. Cone Penetrometer

While investigating this document, it became clear that the cone penetrometer was the least-well-suited sensor type for identifying and locating buried OEW. (Refer to Tutorial Sections 2.1.9 and 2.2.8 for further explanations.) Rather than remove the information already collected, this section describing cone penetrometer vendors was left as-is and attempts to complete an exhaustive vendor list were halted.

To view a summary of the seismic sensor vendor's capabilities, refer to the Seismic Sensor Summary Information Table in Section 4.3.10.

4.1.4.1. Applied Research Associates (ARA)

Albuquerque, NM
Phone: (505) 881-8074
Key contacts: Jim Eddings
Huntsville Division: Jim Boschma,
Phone: (205) 882-9394.

Description
ARA specializes in spatial risk assessment, and environmental site characterization. Their instrument of choice for toxic substance detection is the cone penetrometer, a hydraulic ram that pushes a 3.5 inch dia. instrument into the ground, which can then measure geophysical properties, conductivity of the ground, permeability, groundwater location, or collect soil samples.

They claim there's a way to use the cone penetrometer for detecting OEW, but the technique is still being refined. No word yet on its potential effectiveness. To date it hasn't been deployed for OEW because of danger of pushing the penetrometer head through a live UXO and risking an incident.

One of their new penetrometer head sensors is a side-looking (one-direction only) radar device, which is designed to be left in the ground. They also have tomography software for constructing 2-D and 3-D images for up to a 3 meter radius, depending on the soil conditions.

ARA has many ideas for future projects. Some of the more relevant ones include:

- Incorporate the radar penetrometer and a magnetometer into a small robotic system which can go to the area of interest, insert the penetrometer and build an image.

- Employ gamma activation (similar to neutron activation) for the detection of encased high explosives. Good for "avoiding the negative" identification: if it's not explosive, don't spend the money and time to dig it up. A gamma radiation device can also neutralize dangerous chemicals (anything with a loose oxygen bond) given enough strength.

- They construct airborne sensors from COTS sources. One is called the Small Aerodat Surveillance System Low-Intensity Target Exploration (SASS-LITE), an airborne sensor that can be flown at 35 mph. The other is called the Tethered Aerodat Surveillance System (TASS), which is tethered to a trailer system and collects IR images at a speed of 8 mph. "This has a lot of applications in the OEW area."

- Their unmanned air vehicle (which can fly either remote controlled or autonomously) makes for a very stable sensor platform that can carry hundreds of pounds. They've proposed a program called Multispectral Imagery that makes two airborne passes over the ground: one for daylight photos, and another for IR imaging, combining the two data sets is supposed to yield new insights, but exactly what was not made clear.

Sensitivity: The Cone penetrometer can "see" at most up to 3 meters in certain directions, depending on soil conditions.

Prices: were not provided by ARA.

4.1.4.2 Earth Tech Corp.

18411 Gothard St.
Huntington Beach, CA 92648
Phone: (714) 842-7011
FAX: (714) 842-3735
Contact: Gerry Boehm

Description
Earth Technology offers a full range of cone penetration testing services geared specifically toward hazardous waste remedial investigations and feasibility studies. The CPT test produces a "boring" log without requiring sampling or visual inspection of the soil. (The soil types are derived from a laboratory-developed look-up table, which correlates CPT measurements with conventional borehole sample tests.) An insert in their sales brochure indicates that they have invested in completely new penetrometer and computerized data reduction equipment.

Different cone types are available for different tests. Three different commercial cone types allow the assessment of groundwater conditions. Other cone types enable surveys of conductivity, soil gas, downhole shear wave velocity, and soil samples. With the equipment on-board, computer-generated CPT results are available instantly.

Sensitivity: Not applicable in this industry.

Price: Base rate: $150-210/hr; most tests $6.75/foot (average); data presentation $20/plot, $1500/day minimum.

4.1.4.3 Stratigraphics

439 Taylor Ave.
Glen Ellyn, IL 60137
Phone: (708) 790-4615
FAX: (708) 790-4610
Contact: Andrew Strutynsky

Description
STRATIGRAPHICS has specialized in providing penetrometer testing services for both the geo-environmental and geotechnical industries since 1987. No drilling or consulting services are provided by the company. A second, 28-ton rig is in construction and is scheduled to be operational in late 1994.

Senior engineers run the STRATIGRAPHICS penetrometer rigs. This provides clients a great deal of expertise in the field, as data and samples are acquired. All sub-systems are mounted on the rig to avoid a secondary support vehicle, including field computers, samplers, 5 kW diesel generator, compressor, steam cleaner, grout pump, 200 gallon water tank, and closed circuit television.

They employ a grouting system which seals the open hole during probe advancement, yielding the benefits of reduced soil friction, reducing cross-contamination with other holes, and reducing contamination to operating crew.

Their brochure emphasizes that they only perform the penetrometer service; they don't do consulting or drilling work. Penetrometer end-effectors include electrical conductivity, piezoelectric, and temperature sensors.

Specifications: Not applicable in this industry.

Price: Base price is $175/hr plus $50/setup and $6/foot. Instruments and data processing typically cost an additional $175/hr and $7/ft.

4.1.5. Visible Imaging

For a complete description of visible imaging sensors, refer to the tutorials in Sections 2.1.4, 2.2.4, and 2.3.4. To view a summary of the visible imaging vendor's capabilities, refer to the Visible Imaging Summary Information Table in Section 4.3.5.

4.1.5.1. Environmental Research Institute of Michigan (ERIM)

PO Box 134001
Ann Arbor, MI 48113-4001
Phone: (313) 994-1200
FAX: (313) 994-4630
Key Contact: David Spector

(ERIM also has done work in GPR/SAR. Refer to Section 4.1.3.2.2 for more details.)

Description
ERIM has produced two types of technologies of interest: a ground-penetrating SAR, and the other is multi-spectral imaging. No further information is available.

4.1.5.2. Jet Propulsion Laboratory (JPL)

4800 Oak Grove Dr.
Pasadena, CA 91109
Key Contact: Rob Green
Phone: (818) 354-9136

Description
JPL has developed a second-generation visual instruments called the Airborne Visual and Infrared Imaging Spectrometer (AVIRIS), which operates in both the visible and infrared (IR) range. Refer to Section 4.1.6.10 for more detailed information.

4.1.6. Infrared (IR) Radiometry

For a complete description of infrared (IR) sensors, refer to the tutorials in Sections 2.1.5, 2.2.5, and 2.3.5. To view a summary of the visible imaging vendor's capabilities, refer to the IR Sensors Summary Information Table in Section 4.3.6.

4.1.6.1. AGEMA Infrared Systems Inc.

550 County Ave.
Secaucus, NJ 07094-2607
Phone: (201) 867-5390
FAX: (201) 867-2191
Key Contact: Arthur Stout

Description
AGEMA (formerly AGA) has been building infrared systems since the early 1960's, which it claims is longer than anyone else in the commercial industry. It offers a variety of different systems, ranging from hand-held to an airborne-ready unit, and all work with either the 3-5 μm or 8-12 μm wavelengths (most with both).

All of its systems are mechanically scanned with a mirror in both the vertical and horizontal directions. All but the model 210 offer 12-bit resolution, and can sample at 30 frames per second.

AGEMA offers four systems which are relevant to OEW detection. Their distinguishing features are outlined below:

> **Thermovision® 210** is a lightweight (3.5 lb.), handheld unit that works in the 2-5 μm band.
>
> **Thermovision® 880** is a dual-band IR image scanner with a 12-bit digital image processing system, which is no longer being manufactured. It is used by Lawrence Livermore National Laboratory.
>
> **Thermovision® 900** is a complete digital dual-band system. It includes several high-speed digital storage options and X-windows-based user interface. It is the successor to the 880.
>
> **Thermovision® 1000** has the highest resolution (585 x 400 effective lines), and has the same signal processing capabilities as the 900, but offers only video output. It incorporates a signal processor for better performance. This model can be ordered gimbal-mounted, ready for airborne applications.

AGEMA also makes other handheld units, all v

Sensitivity: AGEMA quotes its s
Change in Temperature (NEΔT).

Thermovision® 210: 0.05° C NE
RS-170 output.

Thermovision® 880: 0.05° C NE
RS-170 output.

Thermovision® 900: 0.07 ° C NE
digital storage options range fron

Thermovision® 1000: 0.1° C NE
resolving commercially availabl
analog video output.

Price:

Thermovision® 210: $19.5K

Thermovision® 880: $55K
comparison purposes only.)

Thermovision® 900: $85K -
options.

Thermovision® 1000: $98K (Ai

4.1.6.2. Amber (A Raytheon Company)

5756 Thornwood Drive
Goleta, CA 93117-3802
Key Contact: Charles H. King Jr., Manager, Sı
Phone: (805) 683-6621
Fax: (805) 964-2185

Description
Amber makes several IR detection products, t
4128, and a handheld unit called Radiance.

The AE-4128 is a high-performance IR imagi
Indium-Antimonide focal plane array, suppo

Such InSb detectors are claimed to possess a high quantum efficiency and wide spectral response (1.9 to 5.5 microns).

The support electronics contains image processing firmware as well as interfacing circuits, and can calibrate the sensor's 16,384 detectors automatically. Their data sheet says the unit is capable of generating more than 1000 frames per second. Its front panel allows for freeze frame, image transformation, and other controls for enhancement, and can be controlled by computer via a serial port.

A second product called Radiance is about the size of a handheld camcorder. Its sensor has a resolution of 256x256, and is sensitive to the mid-IR range (3 to 5 microns). It employs a closed-cycle sterling cooler rather than liquid nitrogen for operation.

Sensitivity: Spectral sensitivity is quoted at 1 to 5.5 µm. Detectivity ($Q = 10^{14}$ photon/cm^2/sec) is quoted as greater than 4×10^{11} cm Hz$^{1/2}$/W.

Price: The AE-4128 sells for $40K (not including lens). The Radiance unit sells for $80K (including lens).

4.1.6.3. Analytical Spectral Devices, Inc. (ASD)
4760 Walnut St., Suite 105
Boulder, CO 80301-2561
Phone: (303) 444-6522
Key Contact: David Hatchell

Description
ASD sells one product, a "spectro-radiometer", which can measure reflectance, transmittance, absorbance, as well as radiance and irradiance in the 350-2500 nm wavelength range. They are primarily designed for the calibration of satellite and high altitude aircraft spectral imaging equipment. ("Irradiance" refers to the amount of energy falling upon a surface. Its measurement is not unlike a photographer's incident light meter, measuring the total light falling upon a subject rather than the light reflected from it.)

The instrument's output is a plot of radiance (or irradiance) vs. wavelength, for a 25 degree field of view. Because the instrument only measures out to 2.5 microns, the amount of thermal radiation it can measure is very low. Mr. Hatchell pointed out that, with thermal IR sensing, one must be careful to only measure thermal radiation rather than thermal reflectance from the illumination source. One way to do this is to only make measurements at night.

Other attributes to their product are rapid data acquisition, high spectral resolution and optical fiber input.

Sensitivity: The noise equivalent radiance (NER) of the units are = 1.9×10^{-6} Watts/cm^2/nm/steradian at 1700 nm, averaged over 4 readings. The wavelength accuracy is +/- 1 nm.

Price: There are three portable units:
350-1050 nm $25K
1000-2500 nm - $49K
Full range instrument: 350-2500 nm $60K

4.1.6.4. Army Research Lab (ARL)

Night Vision Lab
Fort Belvoir, VA
Key Contact: John Buchbach
Phone: (703) 704-1261
email: buchbach@nvl.army.mil

(The Army Research Lab also works on ultra-wideband SAR GPR, MMW, Long- and Short-IR, and seismic sensors, and multi-sensor data fusion, among others. Please refer to these other sections for ARL's work in these areas.)

Description
The ARL Night Vision Lab works with night vision near infrared (IR) technology; typically in the 3-5 micron range rather than the other popular 8-12 micron range. Their job is to assemble systems for mine detection in the field; sometimes they use commercial, off-the-shelf technology, at other times they make or modify their own sensors.

Generally, their sensors are mounted in an unmanned air vehicle, along with radar and LIDAR and is flown at an altitude of 300 feet. Multi-sensor fusion is applied for better discrimination and "...more intelligent results." Both IR ranges are employed because the surface responses to both are different.

Sensitivity and Price: Not Available

4.1.6.5. Bales Scientific

1620 Tice Valley Blvd.
Walnut Creek, CA 94595
Phone: (510) 945-0144
Key Contact: Chip Bishop

Description
Bales sells a sensitive IR sensing element composed of mercury admium telluride, a material sensitive to IR wavelengths between 8-12 microns. 600 of these individual sensors (which are analogous to a pixel in a charge-coupled device) have been assembled and placed under a lens with a 30 degree field of view. The resulting 13" x 12" x 12" IR sensor is capable of distinguishing temperature differences as little as 50 mK (0.05 °C) over a 200 °C temperature range.

Up to 16 of these sensors can be fed into their PC and they can all be displayed in their own windows with their own filtering or convoluting algorithms being applied simultaneously.

Sensitivity: Chip Bishop, the company's representative, quoted the unusual instantaneous field of view (IFOV) metric as being 1.2 milliradians. As stated earlier, the sensor can distinguish as little as 0.05 °C.

Price: Base price is $59.5K, which includes sensor, 486-class PC running Lynix (a Unix variant) and X windows, a 14" SVGA monitor, and basic image processing software.

4.1.6.6. Cincinnati Electronics
7500 Innovation Way
Mason, Ohio 45040
Phone: (513) 573-6275
Key Contact: Paul Tiven

Description
Cincinnati Electronics has spent the last 25 years providing a variety of mid-wave IR sensors, including indium antimonide (InSb), photovoltaic indium arsenide (InAs) and germanium (Ge), and photoconductive mercury cadmium telluride (MCT) sensors. Their sensors come in linear, 2-D, multiplexed 2-D, and space/satellite-qualified lens-and-sensor configurations.

They sell a variety of products, but three are best suited for the job of OEW detection They are:

- IRC-160ST. A cooled-array InSb sensor arranged in a 160x120 configuration. Unit is battery-operated and man-portable. Temperature sensitivity of 0.03 degrees C.

- IRRIS-160ST. Similar to the IRC-160ST (above). The difference is IRRIS has quantitative software built in to give temperature range of image and actual value of center of image. Sensitivity is 0.03 - 0.025 °C.

- IRRIS-256ST, same as the above model except it employs a high-resolution 256x256 array. Sensitivity to 0.02 °C.

- TVS-2500 Employs a 1-dimensional array with a scanning mirror. It's bulkier and has lower resolution than the IRRIS 256 ST, but the unit has software that allows the averaging of successive frames to increase the apparent resolution. Sensitivity is 0.1 °C.

As with all IR cameras, all of the units described above can only work on items near the surface or in shallow water, no more than a few cm in depth for either fresh or salt water.

Sensitivity and Price:

Model	Sensitivity	Price
IRC-160ST	0.03 °C	$39.5K
IRRIS-160ST	0.03 - 0.025 °C	$46.9K
IRRIS-256ST	0.02 °C	$85.7K
TVS-2500	0.1 °C	$48.3K

4.1.6.7. Dorex

954 North Lemon Street
Orange, CA 92667
Phone: (714) 639-0700
Key Contact: Mark Yoshihara

Description
The Dorex DITI-256 thermal imager is a high resolution infrared camera employing a mercury cadmium-telluride sensor tuned to the 3.5 micron wavelength. The unit consists of a 256x256 focal plane array detector, a cooler, and control electronics all contained within a 10" x 7" x 6" case.

The 20 lb. unit contains a fixed-focus lens with a 10 degree field of view. Signal output is RS-170 (standard video coax) or a "digital" format (type not described). The sensor operates at 120 Kelvin (K) rather than the industry-standard 77 K, thereby increasing the life of the refrigerator according to the manufacturer.

Sensitivity: The unit can discriminate 0.07 °C with a 70 dB dynamic range.

Price: $85K for units to be used within the US. (Units destined for foreign countries are build differently.)

4.1.6.8. Geophysical & Environmental Research Corp.
Millbrook, NY
1 Bennett Common
Millbrook, NY 12545
Phone: (914) 677-6100
Key Contacts: S-H Chang, Chief Scientist
Mark Westfield, Exec. V.P.

Description
Geophysical & Environmental Research Corp. designs and manufactures airborne, multichannel IR scanning systems and portable ruggedized IR spectrometers for field and industrial applications. No further information is available.

4.1.6.9. Inframetrics
16 Esquire Road
North Billerica, MA 01562
Phone: (508) 670-5555
FAX: (508) 667-2702
Key Contact: John Keane

Description
Inframetrics sells both IR radiometric and imaging systems, and have done so for the past 15 years. Their Model 760 is a two-piece 25-lb. system that employs a "dual resonant scanning system" (term not defined). It has a built-in LCD display and the ability to store and record several images onto a 3.5" floppy disk.

They also employ and are compatible with the ThermaGRAM brand image processing system that allows image manipulation, evaluation, and data management options at twice the speed and resolution of comparable packages. The system can be programmed to display absolute temperatures, temperature differences, and to compare against a previously stored image.

Inframetrics has also just come out with a new imaging camera, this one weighing a mere 3 lb. including all processing electronics and batteries. No specs on this unit are available.

Sensitivity: The Model 760 can discriminate to 0.1 °C at a resolution of 194 pixels per line.

Prices: The unit is priced between $49K and $60K, depending on options and optics chosen.

4.1.6.10. Jet Propulsion Laboratory (JPL)
4800 Oak Grove Drive
Pasadena, CA 91109
Phone: (818) 354-4321
Key Contact: Robert O. Green, x4-9136

Description
JPL has been involved in the development of instruments for imaging spectroscopy since 1977. A second-generation instrument called the Airborne Visual and Infrared Imaging Spectrometer (AVIRIS) acquires images with swath widths of 10 km having 20 meter ground resolution using detectors having several hundred picture elements. These images comprise 224 contiguous spectral channels from 0.4 to 2.45 mm.

The AVIRIS instrument, while retaining such features as a spectral discrimination of approximately 10 nm/pixel.

Specifications: AVIRIS operates over wavelengths between 0.4 and 2.4 µm. The spectral resolution is 224 contiguous 10 nm wide channels. The surface resolution attained is 30 m across a 20 km wide swath.

Price: Although not for sale, the AVIRIS is available for any qualified user from JPL. It is normally deployed in a NASA ER-2 aircraft at 20 km altitude

Additionally, detector arrays are being developed with sensitivities in the thermal IR region, and usable (> 20%) quantum efficiencies.

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4.1.6.11. Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94551
Phone: (510) 422-1100 (Main number)
Key Contacts: Nancy Del Grande, Phil Durbin
Phone: (510) 422 1010

Description

The LLNL non-destructive evaluation section has been using a specially configured AGEMA 800 dual-band IR sensor for sub-surface object detection. This equipment was originally developed for the detection of weak heat-flow anomalies and for mapping geothermal resources, but recently has been adapted for detecting buried land mines and buried ordnance.

Two bands of imaging are employed for increased sensitivity and noise and surface clutter reduction: 3-5 microns and 8-12 microns. Mr. Durbin of LLNL claims that when these two wavelengths are used together, you get 10 times more information on absolute temperature and surface mapping than if a single channel were used. Tests using the device have revealed ordnance buried at up to 4" in depth in cleared, vegetation-free terrain.

In the five years since the project was started, some patented improvements have been made to the system (mostly in the decluttering and image identification post-processing areas).

The system has been used to survey inert and live mine fields from aerial platforms, and for sea ice mapping in Finland. (Agema is also described in Section 4.1.6.1.)

Sensitivity: No performance specifications were given for the enhanced configuration. Refer to Agema's listing in Section 4.1.6.1 for that product's specifications.

Price: No units are for sale; however, it is possible for anyone to purchase the identical Agema system and they will be happy to help with their custom modifications and post-processing software.

4.1.6.12. Optronic Laboratories, Inc.
4470 35th Street
Orlando, FL 32811-6590
Phone: (407) 422-3171
Key Contact: Wm. Schneider

Description

Optronic Labs makes spectro-radiometers for the measurement of optical radiation in the UV, visible, and IR spectral regions. They are also the supplier of radiometric, photometric, and spectrometric standards and calibration services.

Their representative concluded that their equipment could not be applied to OEW detection. No further details about their products were offered.

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4.1.7. Millimeter Wave (MMW) Radiometry

For a complete description of MMW radiometry sensors, refer to the tutorials in Sections 2.1.6, and 2.3.6. To view a summary of the visible imaging vendor's capabilities, refer to the MMW Radiometry Summary Information Table in Section 4.3.7.

4.1.7.1. Army Research Lab (ARL)

Adelphi, MD 20783-1197
Phone: (301) 394-3130
Key Contacts: Dr. Joe Nemarich, Group Leader
Dr. H. Bruce Wallace, Head of MMW Sensors Branch
(301) 394-2610 (Adelphi)
(410) 278-4321 (Aberdine)

Description

ARL's millimeter wave sensors branch is in charge of basic research to determine MMW's applicability to a range of problems, including imaging, remote object signature identification, and OEW detection. They also review new technology and study basic phenomena such as propagation. (This group was formed by combining two previously separate groups of experts at the Aberdeen Proving Grounds and at Adelphi.)

They typically integrate off-the-shelf MMW radar components with custom hardware and processing algorithms to perform their research. On rare occasions they have assembled radar systems for other customers

Although the topic of UXO has never been explicitly addressed, Dr. Nemarich of ARL claimed that MMW could be applied to this problem. Specific studies as to performance and comparison to other technologies have not been investigated.

Sensitivity and Price: All of their work is still in the research and development phase, and no commercially produced units are available. Sensitivity ratings on their in-house units were not disclosed.

4.1.8. LIDAR

For a complete description of LIDAR sensors, refer to the tutorials in Sections 2.1.7, 2.2.6, and 2.3.7. To view a summary of the LIDAR vendor's capabilities, refer to the LIDAR Summary Information Table in Section 4.3.8.

4.1.8.1. Two-Dimensional

4.1.8.1.1. Kaman Aerospace Corporation

P.O. Box 2
Bloomfield, CT 06002-0002
Phone: (203) 243-7229
Key Contact: Melvin P. French, P.E.
Phone: (203) 243-7085
Chief Test Engineer

FishEye information:
Electro-Optics Development Center
3480 East Britannia Drive
Tucson, AZ 85706-5007
Phone:(602) 889-7000
FAX: (602) 889-0211
Key Contact: Dr. Bobby Ulich
Direct: (602) 295-2101

Description
Kaman has developed a blue-green laser-based LIDAR system called Magic Lantern. In its attempt to commercialize on its defense developments, Kaman's LIDAR is now being commercially offered as the FishEye™ airborne laser fish finder. It's distinguishing feature is that it employs imaging, allowing the user to "see" and distinguish different kinds of fish rather than simply indicating that something was detected.

Kaman believes that the Magic Lantern/FishEye technology can be applied to OEW detection on the bottom of lake beds. They are developing a "bottom-follower", a separate detector that detects the bounced signal from the bottom and uses the timing information to range-gate the sensors (turn on the receiver only during the time that a return is expected) to apply to the next frame.

The penetration depth is determined by the stillness of the water, the scattering coefficient of the water, and the visual contrast of the object on the bottom. If the water is too murky to see through, their LIDAR-based device won't do much better.

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Their LIDAR is still being adapted to lake bed surveying. As of this writing they've done a static experiment with a crane-mounted laser and an experimental bottom-tracking detector. To date it's been proven in principal; in the summer of '94 it is scheduled to be tested in a moving helicopter.

Nominally, you can survey the water as fast as the plane can fly; typically 100 knots with a swath width of 100 ft. At this speed the resolution will be just enough to know if there's something down there. A second, slower pass will then be necessary to gather more information..

Sensitivity: No standard sensitivity metrics for LIDAR have been established. Many factors will determine the penetration depth, including helicopter height and the parameters listed above.

Price: The FishEye™ unit comes with a helicopter mount and sells for $250K.

4.1.8.1.2 Waterways Experimental Station (WES)
Coastal Engineering Research Center Lab
3909 Halls Ferry Road
Vicksburg, MS 39180
WES Main number: (601) 636-3111
Key Contact: Jay Bennett (601) 634-3924

Description

WES has developed and proven a polarimetric LIDAR for surface minefield and OEW detection called the Remote Minefield Detection System (REMIDS). REMIDS emits a laser and measures both the reflectance and polarization of the returned signal, enabling it to classify large, man-made objects and distinguish them from background clutter. Sometimes a third channel is added in the form of an 8-12 μm thermal infrared receiver, to allow the detection of buried objects as well.

The system is typically flown at 200 feet in a manned aircraft and will only work in high-visibility conditions. A 1 μm laser is employed, which means it cannot easily penetrate vegetation or lake beds. It can resolve down to a 3 inch x 3 inch square per pixel; 710 pixels/scan, 350 scans/second. This output is passed through a clustering algorithm which analyzes the relative positions and numbers of the detected objects and infers an air-dropped minefield.

Sensitivity: The system can resolve down to a 3 inch square from a height of 200 feet.

Price: Although not commercially available, the REMIDS system cost approximately $750K for all components, not including design costs.

4.1.9 Multi-Sensor Platforms

4.1.9.1 Army Research Lab (ARL)

Night Vision Lab
Fort Belvoir, VA
Key Contact: John Buchbach
Phone: (703) 704-1261
email: buchbach@nvl.army.mil

Description
The Army Research Lab works on ultra-wideband SAR GPR, MMW, Long- and Short-IR, and seismic sensors, and multi-sensor data fusion, among others. For individual descriptions, please refer to the appropriate sections:

Infrared	4.1.6.4
MMW	4.1.7.1
Ultra Wide Band Radar	4.2.3.1.1
Seismic Sensors	4.2.4.1
LIDAR	4.2.7.1

4.1.10 Other Related Technologies

Although none of the technologies listed in this section can be classified as a sensor, they do provide significant advancements in other aspects of sensor data collection that would allow the extraction of more information when used with conventional sensors.

4.1.10.1. Ballena Systems Corp.

5820 Stoneridge Mall Rd. Suite 205
Pleasanton, CA 94588
Phone: (510) 460-3740
Contact: Dr. Kendall Casey
Fax: (510) 460-3751.

Description

Ballena is a small company. Historically they've been contractors and a consulting house for DoD and DoE. A few years ago they got involved in the cleanup of Kaho'olawe, HI. Since that time they've been active in the ordnance remediation field from a technical point of view.

They have expertise in all areas relevant to OEW detection: sensors, data fusion/signal processing, mapping/GIS, and a "novel application of data collection," which means unique math techniques on sensor data processing. Their strengths seem to be in writing analysis reports rather than in developing technologies.

Ballena submitted ten proposals in response to a recent OEW MCX Broad Area Announcement (BAA). The proposals included technologies such as:

- Neutron activation - Ballena has proposed studying the use of Neutron-Activation methods for the detection of chemical surety material (CSM). To date, they have not developed any technology to do so.
- Advanced signal processing of magnetometer sensor data using wavelets, to help isolate the OEW from subsurface clutter. The processing algorithms would also allow for an estimation of object depth from OEW signatures.
- Sensor fusion techniques to mathematically combine the outputs of sensors which exploit different physical phenomena.
- An integrated GIS mapping system

- Non-linear EM - Ballena has proposed investigating the potential utility non-linear electromagnetic interactions for improving the detection of buried ordnance. They claim that developing such technology will result in an improvement in both false positive and false negative detections.

"For ordnance purposes, existing sensors are sensitive enough; the problems are with collection, mapping, fusion, etc." Their workhorse sensors include GPR and electromagnetic induction. Specific sensors mentioned in conversation were the Schonstedt magnetometer and EG&G Geometrics instruments. (During a conversation early in 1993, Dr. Casey remarked that neutron activation for the detection of underground mines was looked at, but they weren't convinced that it's practically usable for OEW shells or artillery.)

Sensitivity: The company does not make sensors.

Price: Fees for their services vary: rough unit is $250K/workyear (with a typical task requiring 2.5 to 3 experts).

4.1.10.2. Chemrad Tennessee Corp.
1055 Commerce Park Drive, Suite 104
Oak Ridge, TN 37830
Phone: (615) 481-2511
FAX: (615) 483-0941
Key Contacts: Mike Blair, Bob Hifield

Description
The USRADS® (UltraSonic Ranging And Data System) is a man-portable position and data recording system used for UXO walkover surveys with a variety of detectors, including magnetometers, terrain conductivity meters, and radiation detectors. It automatically records the surveyor's location (to within +/- 6"), along with up to six channels of detector data each second to provide high-density and accurate sampling. The data are displayed in real-time on the field computer so dynamic protocol changes may be made as needed to ensure complete coverage. The real-time display also aids in on-line quality assurance of the survey results.

Chemrad sells and rents the USRADS system, as well as provides USRADS survey services. Chemrad was the only company to receive multiple awards for the UXO technology demonstration at the Jefferson Proving Ground in 1994.

4.1.10.3. Dean Consulting & Research Inc.
Norwich, VT
Phone: (802) 649-2202
Key Contact: Arnold Dean

Description
DCRA is rumored to have experience with an airborne EM system and with impulse radar, although no one at the consulting firm has responded to phone messages.

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4.2. EMERGING SENSOR TECHNOLOGY PRODUCTS

The emerging sensor technologies listed in this section are organized to reflect the structure of the Tutorials Section 2.3, and lists who is working with promising technology that exists in the laboratory or is being field-proven and has not yet been commercially deployed.

The information in this section is organized as follows and includes products of the companies listed in the sub-paragraphs:

- 4.2. Emerging Sensor Technology Products
  - 4.2.1. Magnetometers
    - 4.2.1.1. Optically Pumped Magnetometers
      - 4.2.1.1.1. Quantum Design/Quantum Magnetics Corp.
    - 4.2.1.2. Superconducting Quantum Interference Device (SQUID) Magnetometers
      - 4.2.1.2.1. 2G Enterprises
      - 4.2.1.2.2. Applied Physics Systems (APS)
      - 4.2.1.2.3. Coastal Systems Station
      - 4.2.1.2.4. Conductus, Inc.
      - 4.2.1.2.5. FIT
      - 4.2.1.2.6. Loral Defense Systems
      - 4.2.1.2.7. Quantum Design/Quantum Magnetics Corp.
    - 4.2.1.3. Three-Axis Fluxgates
      - 4.2.1.3.1. Applied Physics Systems (APS)
      - 4.2.1.3.2. Coastal Systems Station
    - 4.2.1.4. Electron Tunneling Magnetometer
      - 4.2.1.4.1. Jet Propulsion Laboratory
    - 4.2.1.5. Fiber-optic Magnetometers
      - 4.2.1.5.1. Naval Research Laboratory (NRL)
      - 4.2.1.5.2. Optical Technologies Inc.
  - 4.2.2. Electromagnetic Induction
    - 4.2.2.1. Ballena Systems Corp.
    - 4.2.2.2. University of Arizona
    - 4.2.2.3. AC Susceptibility
      - 4.2.2.3.1. Quantum Design/Quantum Magnetics Corp.
  - 4.2.3. Ground-Penetrating Radar
    - 4.2.3.1. Ultra-Wideband Synthetic Aperture Radar (UWB-SAR)
      - 4.2.3.1.1. Army Research Lab (ARL)
      - 4.2.3.1.2. Battelle, Inc.

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The following sensor technology categories do NOT appear in this section because vendors doing research in these technologies have not been identified:

Proton Precession Magnetometers
Overhauser Effect Magnetometer
Narrow-Band GPR
Cone Penetrometer
Transient Sensors
Seismic Sensors
Ultrasonic Sensors
Infrared Radiometry Sensors
Millimeter Wave (MMW) Radiometry Sensors

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4.2.1. Magnetometers

The magnetometer technologies described in this section are still in the research and development stage, and are not yet available off-the-shelf. Five varieties of magnetometer are covered: SQUID, Overhauser Effect, 3-Axis fluxgates, electron tunneling, and fiber-optic magnetometers.

(Also refer to Section 4.1.1 for a listing of readily available magnetometer products.)

4.2.1.1. Optically Pumped Magnetometers

4.2.1.1.1. Quantum Design/Quantum Magnetics Corp.
11578 Sorrento Valley Road Suite 30
San Diego, CA 92121
Phone: (619) 481-4400
FAX: (619) 481-7410
Key Contact: Dr. Bill Avrin

(Quantum Design also makes SQUID magnetometers and an advanced EM sensor. For more information refer to Sections 4.2.1.2.7 and 4.2.2.3.1.)

Description
Quantum is actually two separate companies; the only thing they have in common is that they both employ SQUID technology. Both divisions claim to offer the most advanced commercial SQUIDs available.

Although they currently offer no products incorporating optically pumped magnetometers, the company has proposed a proof-of-concept device called a dead-zone-free optically pumped magnetometer, which eliminates the "blind spot" characteristic of such sensors. They have SBIR Phase I funds and are currently working with the Naval Research Laboratory to construct a demonstration unit.

Sensitivity and Price: These ideas are in the early stages of development; therefore none of these parameters are known.

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4.2.1.2. Superconducting Quantum Interference Device (SQUID) Magnetometers

4.2.1.2.1. 2G Enterprises
297 Independence Ave. Suite 1C
Mountain View, CA 94043
Phone: (415) 965-0500
Key Contact: Robert Goodman

Description
2G Enterprises is a reseller of rock magnetometer products whose electronics are manufactured by Applied Physics Systems (APS) and whose dewars are manufactured by a company named William S. Goree Corp. (Refer to Sections 4.1.1.3.1, 4.2.1.2.2, and 4.2.1.3.1 for more on APS' other products.)

Superconducting rock magnetometers (SRM) are tools designed for geophysicists which allow them to analyze the magnetism of cored rock samples they collect. These samples are placed into the magnetometer chamber to determine directions and strengths of the magnetic fields. This information can be used along with other data to determine the age of the rock. This has been useful in the study of continental drift.

These systems are now using very sensitive DC SQUID sensors that have very low noise and high sensitivity.

Sensitivity: 4×10^{-9} EMU RMS $\sqrt{\text{Hz}}$ for 4.2 cm access

Price: A complete 3-axis SRM (consisting of 3 measurement axis with 3 SQUIDs and 3 sets of SQUID electronics) sells for $110K - $115K.

4.2.1.2.2. Applied Physics Systems (APS)
897 Independence Ave. Suite 1C
Mountain View, CA 94043
Phone: (415) 965-0500
Fax: (415) 965-0404
Key Contact: Bob Goodman

Description
APS is primarily a fluxgate magnetometer company. (Refer to Sections 4.1.1.3.1 and 4.2.1.3.1 for more on their fluxgate magnetometer line.) In addition, they have extensive experience in building SQUID magnetometer systems.

APS makes a low-noise, high-accuracy DC SQUID magnetometer system that consists of a DC SQUID sensor, cryogenic probe, display/console, and processor electronics.

(See also Section 4.2.1.2.1 for other SQUID products manufactured by APS and sold under the "2G Enterprises" name.)

Sensitivity: Noise level is $5 \times 10^{-6}\ \Phi_0$ rms/$\sqrt{\text{Hz}}$.

Price: $11.8K for the entire system.

4.2.1.2.3. Coastal Systems Station (CSS)
Dalgren Division
Naval Surface Warfare Center (NSWC)
6703 W. Highway 98
Panama City, FL 32407-7001
Phone: (904) 234-4281 or 4660
Key Contact: Gary Kekelis

(CSS also works with advanced 3-axis fluxgate magnetometers. Refer to Section 4.2.1.3.2 for more details.)

Description
For the past 25 years, this R&D arm of the Navy has experimented with and has done development on every type of remote sensor mentioned in this sourcebook except GPR. Their main goal is the underwater (particularly salt water) detection of mines and submarines, although they have also constructed gradiometers out of every conceivable magnetometer type and have constructed several multi-sensor platforms for improved discrimination in underwater object detection.

Their greatest advancement so far has been in the development of sensitive DC SQUIDs, which can be used in an airborne configuration with a sensitivity of 10^{-3} nT/ft. This system is fully packaged for underwater surveillance. It can be used directly for underwater surface or buried ordnance detection. A new, high-performance airborne developmental SQUID should be ready in September 1994, designed to be towed behind a helicopter 20-50 feet off the ground. Although the unit would have difficulty detecting a single 50 mm round it will excel in detecting groups of 50 mm shells or large underground barrels.

One advantage of a highly sensitive airborne SQUID over an airborne GPR is that the soil is transparent to a SQUID, making for more effective location of exposed and buried object in soils possessing a high conductivity value. A unique aspect of their sensors is that they measure 5 independent gradients; simultaneously measuring the three-dimensional profile and the locations of an underwater mine. These unique measurements are used by their in-house post-processing software to reject background noise, localize a target to get range and bearing exactly, and determine 3 components of a magnetic moments.

The Navy has been known to employ seismic sensors in conjunction with their magnetometer sensors to help them distinguish between OEW and, say, a discarded cartwheel. This technique has successfully reduced their false alarm rate.

Sensitivity: Their DC SQUIDs have sensitivity of 10^{-3} nT/ft.

Price: Although none of their sensors are commercially available, the DC SQUID magnetometer tends to be expensive; in the neighborhood of \$500K-\$1M to construct one.

4.2.1.2.4. Conductus, Inc.

969 W. Maude Ave.
Sunnyvale, CA 94086
(408) 737-6759
(408) 732-3181
Key Contact: Stephen Garrison

Description

Conductus has fabricated a 1x1 cm^2 integrated DC SQUID and pickup coil package that they claim is the most sensitive SQUID component available. They also sell an "iMAG" 3-channel SQUID controller and flux-locked loop electronics package so the user can assemble a complete magnetometer. Two types of sensors are available:

The 77K SQUID which is cooled by liquid nitrogen and has a sensitivity of < 300 fT

The 4K SQUID which is cooled by liquid helium

Each sensor requires the purchase of a flux-locked loop (FLL) and cable for each input channel.

Nailing them down for exact performance specs was difficult, since the performance of a system heavily depends on the current applied in the modulation coil, signal amplitude desired, and other system parameters defined by the user. They constantly disclaimed that they are selling magnetometer components, not complete systems. They are, however, on record for claiming that their systems' noise performance is better than their competitor's (Quantum) by a factor of two.

Conductus also sells conventional gradiometers and magnetometers, and will assemble a custom magnetometer system to a customer's specific needs.

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Sensitivity: None given; depends on system design

Prices

iMAG 3-channel SQUID controller	$2,995
77K SQUID magnetometer	$4,000
4K SQUID magnetometer	$1,500
FLL (one needed for each channel)	$2,500

4.2.1.2.5. Forschungsgesellschaft für Informationstechnik mbH (FIT)
Bodenburger Str. 25/26
Postfach 1147
D-3202
31158 Bad Salzdetfurth
Germany
Phone: (0 50 63) 89-580
FAX: 011 49 5063 89-666
Key Contact: Prof. Dr.-Ing. J. H. Hinken

Description

FIT claims to be the only European company that produces high-temperature (77K - liquid nitrogen temperature) RF SQUID sensors. Their main market is for close-proximity detection, but they claim the units are also well suited for remote sensing. (In fact, they have configured two systems tailored for this purpose for customers.) They also make a "field distribution" measuring system (quotations are theirs), which is essentially a complete magnetometer encased in a magnetically shielded chamber.

They offer two SQUID sensors (the HS20 and HS07) and a complete SQUID magnetometer system (the HM1). Some of their SQUIDs were flown on the Space Shuttle Discovery in 1993.

Sensitivity:
HS20 RF Sensor: 2×10^{-3} nT/$\sqrt{\text{Hz}}$
HS07 RF Sensor: 0.7×10^{-3} nT/$\sqrt{\text{Hz}}$

Price:
HS07 Sensor: DM 5,000.
HS20 Sensor: DM 1,500
HM1 Complete System (including control unit, shield, cryogenic probe, and other apparatus): DM 28,000.
Prices for the field distribution system are application-specific. A special form must be filled out to receive a quote.

4.2.1.2.6. Loral Defense Systems (Formerly IBM before 3/1/94)
9500 Godwin Drive
M/S 102-078
Manassas , VA 22110
Key Contact: Fred Sulmer
Phone: (703) 367-4374

Description

IBM has just built a new type of room-temperature SQUID magnetometer for the Navy, said to be "...5-10 times better than anything else out there" (according to Dr. Andy Hibbs of Quantum Design). Their new technique for improving sensitivity involves a new way to connect feedback loops to cancel spurious signals, and the employment of 5 gradiometers and 3 magnetometers in one system to increase certainty, speed, and object identification.

The boat-towed system was designed specifically for the Navy's NSWC/Coastal Systems Station in Panama City for use in detecting mine fields in the ocean. Although the performance specifications are classified, their requirement of finding 75% of all mines to within +/- 60 feet were exceeded. Since the field test in 1989, refinements in the technology have improved the sensitivity by an order of magnitude.

IBM/Loral is now doing research on two other related sensor types: one that uses liquid nitrogen (which operates at an absolute temperature of 77 K, instead of liquid helium types which operate at 4 K). They are also working on a room temperature gradiometer, which can be used by a swimmer. This is the kind of device that could be adapted for field use easily. Because all location information is given immediately and accurately, this device poses less danger to the operator.

For a field clearance application, they envision putting one of their sensors on a stick which is carried by a remotely piloted vehicle.

Sensitivity: Classified, but it can be assumed that these are the most sensitive magnetometers currently in existence.

Prices: Depends on use. About $750K can purchase a unit whose power supplies and processing electronics are remotely tethered to the sensor; Navy units which required one single integrated unit cost $860K.

4.2.1.2.7. Quantum Design/Quantum Magnetics Corp.
11578 Sorrento Valley Road Suite 30
San Diego, CA 92121
Phone: (619) 481-4400
FAX: (619) 481-7410
Key Contact: Dr. Bill Avrin

(Quantum Design is also just getting into the optically pumped magnetometer business, and have developed an advanced EM sensor. Refer to Sections 4.2.1.1.1 and 4.2.2.3.1 for more details.)

Description
Quantum is actually two separate companies; the only thing they have in common is that they both employ SQUID technology. Quantum Design makes a turnkey SQUID chamber for measuring small (on the order of a few cubic millimeters) samples for materials science research. Quantum Magnetics is a research group that also deals with government contracts. Both divisions claim to offer the most advanced commercial SQUIDs available. Right now Quantum Magnetics is working on a military system for mine detection employing SQUIDs. They will also assemble an entire instrument based on the application.

Quantum Magnetics will sell the components to their stand-alone, helium-cooled DC SQUID units (which are essentially input sensors and converters that provide an output voltage proportional to the sensed magnetic field). They also will assemble custom systems and consult. According to Dr. Bill Avrin from Quantum, "All user-assembled systems must be carefully machined to take best advantage of the SQUID sensor.".

They are also working on several other ideas in the future, which are worthy of noting here:

- They've made 3-axis SQUID gradiometers that can not only detect fields in any orientation, but can also self-correct for rocking motion in the flight vehicle.

- They are considering constructing a high-temperature superconductor SQUID gradiometer. Although these wouldn't be able to match the sensitivity of a standard liquid-helium-cooled SQUID (perhaps to 150 fT/√Hz), it would be small and light enough to be used as a handheld device.

- They are considering the use of nuclear magnetic resonance (NMR) technology to distinguish chemical fingerprints of ordnance below the surface (even if completely encased). Because it would take several seconds to perform the identification, the most likely usage scenario would be to detect the presence of something using conventional magnetometer techniques, and then employ the NMR system to identify objects in areas that require further investigation. (It's also an ideal technology for screening luggage for non-metallic bombs at airports.)

- Another technology, AC susceptibility, works on the principle that most items will become partially magnetized when exposed to a magnetic field. The amount of magnetization retained varies for each substance, and therefore can be employed as an identification signature. Dr. Avrin claims that they are world experts on this technology.

- They've solved the problem of unmanageably large gradiometers (made that way to increase their sensitivity). Their three-SQUID gradiometer successfully combines the readings of these non-adjacent sensors without having to have the 3 probes enclosed in the same cryogenic environment. (The new problem is that they're now harder to adjust.) This was produced as a joint project with IBM.

- They have solved the problem of electromagnetically noisy helicopter interference by employing a very long tow cable.

Sensitivity: Their SQUIDs are rated at 5 $\mu\Phi_0/\sqrt{Hz}$. The actual performance of gradiometer systems in motion is classified. A good gradiometer can go to a few $fT/\sqrt{Hz}$ (if the conditions are right).

Price: The price for a complete system is difficult to predict due to the custom nature of each, but a ballpark figure was $10K parts for a 1-channel system; $15-20K parts for 2 channels. An assembled system costs many millions of dollars because each is essentially a research project.

4.2.1.3. Three-Axis Fluxgates

4.2.1.3.1. Applied Physics Systems (APS)
897 Independence Ave. Suite 1C
Mountain View, CA 94043
Phone: (415) 965-0500
Fax: (415) 965-0404
Key Contact: Bob Goodman

(APS also makes SQUID magnetometers and benchtop fluxgate magnetometers. Refer to Sections 4.2.1.2.2 and 4.1.1.3.1 for more information on these products.)

Description
APS makes a very small 3-axis fluxgate magnetometer (model APS533) packaged in a fiberglass cylinder of dimensions 0.725" dia. x 1.5" long. They also make a

somewhat larger system (model APS534) that is rectangular, 0.75" x 0.75" x 2.5".

The system provides 3 analog output voltages proportional to the magnetic field in three orthogonal directions. The systems operate from input voltages of +/- 5 VDC and consume a total power of 200 mW. These instruments can be incorporated into systems where magnetic field detection and/or measurement is required.

Sensitivity: Noise level is less than 10^{-6} Gauss rms/√Hz. Range is 1 μGauss to 1 Gauss.

Price: \$2K - \$3K each.

4.2.1.3.2. Coastal Systems Station(CSS)
Dalgren Division
Naval Surface Warfare Center
6703 W. Highway 98
Panama City, FL 32407-7001
Phone: (904) 234-4281 or 4660
Contact: Gary Kekelis

Description
For the past 25 years, this R&D arm of the Navy has experimented with and has done development on every type of remote sensor mentioned in this sourcebook except GPR. Their main goal is the underwater (particularly salt water) detection of mines and submarines, although they have also constructed gradiometers out of every conceivable magnetometer type and have constructed several multi-sensor platforms for improved discrimination in underwater object detection.

Their fluxgate sensors have been looked at by the Army specifically for FUDS cleanup activity; the advantages here are that a region can be swept through quickly and that items in bushy or wooded areas can still be detected without having to painstakingly cover every square inch from above. (Buried objects can be detected from as far as 20 feet to the side.) They are currently making a new type of fluxgate short-baseline magnetometer (along with IBM) that will achieve a sensitivity of 0.1 nT/ft and will measure all five independent spatial gradients.

Opportunities to work with the Army for either technology transfer or joint sensor development are welcomed.

Sensitivity: Their DC SQUIDs have sensitivity of 10^{-3} nT/ft.
Their fluxgate short-baseline magnetometer has a sensitivity of 0.1 nT/ft.

Price: Although none of their sensors are commercially available, they've been able to construct a fluxgate gradiometer for less than $75K.

4.2.1.4. Electron Tunneling Magnetometer

4.2.1.4.1. Jet Propulsion Laboratory (JPL)

Microdevices Laboratory
4800 Oak Grove Drive.
Pasadena, CA 91109
Phone: (818) 354-0982
Key Contact: Linda Miller

The microdevices laboratory (MDL) at JPL has developed a low-power, expendable, micromachined electronic tunneling magnetometer with a sensitivity of 0.001 gamma and a size of less than 0.5 in^3. The key components of this magnetometer are fabricated on a silicon wafer using MDL's VLSI technology that is low in weight, volume, and power consumption. This micromachined magnetometer is being developed for the Navy for its anti submarine warfare applications.

Many different sensors have been developed using this technology, including magnetometers, accelerometers, uncooled IR sensors and seismometers. It could also be developed into a high-sensitivity, low-cost handheld magnetometer for OEW site characterization.

Sensitivity: 0.001 gamma.

Price: The VLSI chips should cost about $5.00 apiece in large quantities.

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4.2.1.5. Fiber-optic Magnetometers;

4.2.1.5.1. Naval Research Laboratory (NRL)
Optical Science Division
Department of Optical Techniques
Code 5674
Washington D.C . 20375-5000
Phone: (202) 767-5369
Key Contact: Dr. Frank Bucholtz

Description
The Naval Research Laboratory has just deployed 8 of their newly developed Underwater Dual-channel 3-axis fiber-optic vector magnetometers off the coast of Norway. These units offer completely remote operation via an electro-optical cable for underwater operation. 3-axis vector magnetometers can give both the strength and the direction of sensed magnetic fields, allowing the operator to better "see" the orientation of the object and therefore to help in identifying it. A long cylindrical object, for example, would have an identifiable vector field signature with a 3-axis sensor.

Dr. Bucholtz estimates that if the sensor were to be adapted for airborne use (assuming 30 m off the ground, and 0.1 nT of probing energy and unity SNR), the detection threshold would be 3,000 nT/m^3. "It couldn't detect a bolt from the air, but could detect a Toyota engine."

Because they are just now ending their research phase, the fiber optic magnetometer is not yet available, although it is "just about ready for commercial development." Post-processing software was <u>not</u> developed in-house; rather they consulted with Bill Eaton at Hughes (Fullerton, CA (714) 732-6940.)

Sensitivity: Not provided.

Price: An array of 8 would cost in the neighborhood of $20-30K for each 3-axis sensor.

4.2.1.5.2. Optical Technologies Inc. ("OPTECH")
360 Herndon Parkway, Suite 1200
Herndon, VA 22070
Key Contact: Robert Einzig, Dave Bennet
Phone: (703) 478-0844

Description
OPTECH Inc. specializes in fiber optic sensor development and manufacturing. They are currently developing a field testable 3-axis fiber-optic, backpack-

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mounted magnetometer with noise stability and low drift. This program is currently funded by U.S. Navy EOD Technology Center.

The first prototype was completed in January of 1994 and delivered to the EOD Tech center at Indian Head, MD for evaluation. Future iterations should improve performance beyond their current 1.0 gamma sensitivity to perhaps 0.5 gamma. Another improvement with which they will experiment is using one laser to feed six sensors, for a cost-effective approach to increasing sensitivity.

Sensitivity: Recent tests rate the prototype unit at 1.0 gamma RMS/$\sqrt{}$Hz. (With a SNR of 1, that would be the minimum detectable signal.)

Price: As it is still a prototype, no price was available.

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4.2.2. Electromagnetic Induction

4.2.2.1. Ballena Systems Corp.

5820 Stoneridge Mall Rd. Suite 205
Pleasanton, CA 94588
Phone: (510) 460-3740
Key Contact: Dr. Kendall Casey
Fax: (510) 460-3751.

Description

Ballena has proposed investigating the potential utility non-linear electromagnetic interactions for improving the detection of buried ordnance. They claim that developing such technology will result in an improvement in both false positive and false negative detections.

(For a more complete description of Ballena, refer to Section 4.1.10.1.)

4.2.2.2. University of Arizona

Department of Mining and Geological Engineering
Building #12
Tucson, AZ 85721
Phone: (602) 621-2439
FAX: (602) 621-8330
Key Contact: Dr. Ben K. Sternberg

Description

A series of high-resolution electromagnetic (EM) systems have been developed in frequency ranges of 30 Hz to 30 kHz, 1 kHz to 1 MHz, and 30 kHz to 30 MHz. These systems measure the ellipticity of magnetic field from a nearby transmitter. Key features of these systems include:

1) Rapid surveys to allow dense spatial sampling over a large area,
2) High-accuracy measurements which are used to produce a high-resolution image of the subsurface,
3) Measurements which have excellent signal-to-noise ratios over a wide bandwidth,
4) Large-scale physical modeling to produce accurate theoretical responses over targets of interest in shallow-geophysics surveys,
5) Rapid neural network interpretation at the field site, and
6) Visualization of complex structures during the survey.

The current systems are in the research phase and are available for demonstration surveys, but presently not for commercial application. They will be investigating technology transfer to the private sector shortly.

Sensitivity: Dr. Sternberg wasn't able to provide a sensitivity rating comparable with reported specs of other vendors, but did claim a location accuracy of 0.1% in both depth and horizontal location.

Price: N/A.

4.2.2.3. AC Susceptibility

4.2.2.3.1. Quantum Design/Quantum Magnetics Corp.
San Diego, CA
Phone: (619) 481-4400
FAX: (619) 481-7410
Key Contact: Andrew B. Hibbs

(Quantum Design is also into SQUIDs and is just getting into the optically pumped magnetometer business. Refer to Sections 4.2.1.2.7 and 4.2.1.1.1 for more details.)

Description
Quantum is actually two separate companies; the only thing they have in common is that they both employ SQUID technology. Both divisions claim to offer the most advanced commercial SQUIDs available.

Quantum is also working on several ideas for the future (refer to Section 4.2.1.2.7 for others), one of which is AC susceptibility. This works on the principle that most items will become partially magnetized when exposed to a magnetic field. The amount of magnetization retained varies for each substance, and therefore can be employed as an identification signature. Dr. Hibbs claims that they are world experts on this technology.

The technique is claimed to be far more powerful than DC magnetometers; measuring both in-phase and out-of-phase signals that reveal physical properties of the object. The conductivity of the soil is not a hindrance, and the signal processing part of the system could be programmed to filter it out.

Currently, the 25 existing AC Susceptibility systems they've manufactured have been sold to university research departments for materials classification purposes. The technology could be applied toward OEW detection; they have already proposed (in conjunction with Geo-Centers) a helicopter-towed magnetometer that would take readings at 75 feet (above the tree lines). Their calculations indicated it would be able to detect a 500 lb. shell to a depth of 15 feet underground. (Other problems, such as the noise generated by the helicopter, would still have to be worked out.)

They can apply external field and read simultaneously.

Sensitivity: The technology has not been applied for ground penetration yet, but they calculated that a 500 lb. bomb could be detected at a depth of 15 m. (No comparable sensitivity measurements were offered.) The sensitivity of their university lab classification systems was not offered.

Price: The university lab classification system goes for $100K each.

4.2.3. Ground-Penetrating Radar

This section covers GPR technologies still in the research phase, which can be applied to land-based and/or airborne configurations. The technologies include ultra-wideband SAR, harmonic radar, and interferometric impulse radar.

For a tutorial on emerging GPR technologies, refer to Section 2.3.3

4.2.3.1. Ultra-Wideband Synthetic Aperture Radar (UWB-SAR)

4.2.3.1.1. Army Research Lab (ARL)
AMSRL-SS-SG
Adelphi, MD 20783-1197
Phone: (301) 394-2530
Key Contacts: John McCorkle, Jeff Sichina , Carl Kapra

Description
John McCorkle mentioned that his division of ARL is working on two Ultra Wideband Radar systems in conjunction with MIT Lincoln Laboratory and the University of Florida.

The first ranges from 40 MHz to 1 GHz and operates on a pulse strength of 2.5 megawatts (MW). A second system, which will eventually be slated for airborne use, will put out 10 MW of power and operate between 20 MHz and 3 GHz. It will be a full 3-D SAR, and an early iteration has already been successfully used for foliage penetration. It should be fully functional by Fall of 1994.

Sensitivity and Price: Although he admitted that the figure wasn't currently meaningful, a SNR of 10 dB was quoted. No price was offered.

4.2.3.1.2. Battelle, Inc.

505 King Ave.
Columbus, OH 43201
Key Contact: Dr. Keith Shubert
Phone (614) 424-4916

(Battelle is also developing a multi-sensor platform. Refer to Section 4.2.9.1 for details.)

Description
Battelle is teaming up with the Electroscience lab at Ohio State University to develop a low-frequency, high-resolution airborne GPR with special SAR;

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techniques to allow deeper penetration and better discrimination between man-made objects and natural buried debris.

Funded by the U. S. Army Environmental Center, it is strictly a research project and is still in the planning stages. It is hoped that they will be able to test-fly a prototype system in summer or fall of '94. A ground-towed system is also being planned.

The GPR operates in the low frequency range, from 50 to 500 MHz. Once their system is proven, they expect the price to be competitive with other airborne GPR systems.

Sensitivity and Price: As the devices are still in the research stage, no information is available.

4.2.3.1.3. Mirage Systems

Lakeside Dr.
Sunnyvale, CA 94086
Phone: (408) 733-3200
Key Contacts: Roger Druhan, George Moussally

Description
Mirage currently has a DoE proof-of-concept contract developing a ground-towed GPR for imaging underground targets like 50-gallon drums. They claim it is a high-end GPR that produces 3-D images and employs exceptional post-processing algorithms based upon fuzzy logic and neural network technologies for target recognition.

The system is currently under construction, and is scheduled to be deployable by Fall of '94. It is currently ground-based, but have proposed building an airborne version. They are willing to work with the Corps of Engineers to optimize the platform for airborne surveying.

Sensitivity: Not offered.

Price: Not yet applicable.

4.2.3.1.4. MIT Lincoln Laboratory
Wood Street
Lexington, MA
Key Contact: Ted Groesch
Phone: (617) 981-0130
Key Contact: Dr. Serpil Ayasli
Phone: (617) 981-5500 x7478
Internet Address: serpil@ll.mit.edu

Description

In the past MIT Lincoln Lab has helped develop foliage-penetrating radar (FPR) and a rail-based SAR. Currently, Lincoln Lab is performing joint development work on an Ultra-Wide-Band SAR technology with a number of entities, including ARPA, FOA, and the Army Research Lab. (Also refer to "Army Research Lab" Sections throughout this document for more information.)

The project, currently in the research phase, is code-named "Steel Crater" and will be an airborne SAR system with a bandwidth of 50 MHz to 2 GHz. The receiver is currently being tested on the roof of the old Harry Diamond Lab, and the system will first be tested on a 150 foot crane to test out ultra-wideband (UWB) response to buried objects, and "...to trace out 1- and 2-D apertures." The impulse power will be on the order of tens of watts.

The SAR is currently in the planning stage, a couple of years away from actualization.

Lincoln Lab is also in charge of data reduction for the Yuma Proving Grounds GPR field test results which took place in 1993.

Sensitivity and Price: Not available.

4.2.3.1.5. Ohio State University
Electroscience Lab
Key Contact: Dr. Jonathan D. Young
Phone: (513) 292-6657

Description

The Electroscience Lab at Ohio State University has been doing GPR research since 1968, and has since pioneered the use of GPR for land mine detection and identification, and buried utility location (including plastic pipes). They are currently working on a helicopter-borne OEW research project with Battelle that is scheduled for demonstration in the Fall of '94. The unit was described as a low-frequency, high-resolution airborne GPR with special SAR techniques.

The research concerns the radar signature of buried ordnance -- being able to distinguish between unexploded ordnance, ordnance fragments, rocks, or a buried drum. They are using neural network technology for the signature identification. They are also developing the radar antennas that give frequency gain and bandwidth needed for airborne SAR systems. Funded by the U. S. Army Environmental Center, it is strictly a research project and is still in the planning stages.

Unique to their system that in conjunction with buried utility research and military research project, they've measured soil parameters in more than 1000 areas in US as part of a first step toward standardized performance measurements across different vendors and models.

For further reading about their GPR techniques, refer to Chapter 9 of the book "Time Domain Measurements In Electromagnetics" edited by Edwin Miller, published by Van Noestrin/Reinhold, 1986.

Sensitivity: Dr. Young said he couldn't discuss performance metrics since an airborne version hasn't yet been built. Their goals are the detection of small ordnance to a depth of 1 m, and large ordnance to a depth of 7m in all soils.

Price: Not yet applicable.

4.2.3.1.6 Time Domain Systems, Inc.

4825 University Square
Suite 3
Huntsville, AL 35816
Phone: (205) 837-6662
FAX: (205) 837-6293
Contacts: Mark Barnes, Larry Fullerton

Description
Time Domain Systems has been an R&D company since 1987 which develops products and licenses them to end users. They claim to have taken a unique approach to solve common GPR problems, in that they incorporate ultra wideband correlator receivers similar to FM-CW GPRs for reduced noise, and a patented antenna that enhances post-processing to yield a more sensitive GPR which operates at considerably lower wattage and increased sensitivity than conventional systems.

Whereas conventional GPRs tend to transmit uniform pulse trains (resulting in potential electromagnetic interference (EMI) problems, TDSI's approach is to employ a time domain correlator receiver (which is a form of matched filter) and a patented dither filtering technique, which reduces harmonic-induced EMI and makes filtering and noise-elimination techniques more effective. TDSI's proprietary antenna design also is responsible for more efficient energy transfer, can be operated at varying distances from the ground, and the same transmitted waveform can be used regardless of the electrical properties of the ground. (Other GPR systems must fine-tune their transmitted pulses to match the ground type; this is partly responsible for the different penetration depths.)

Another distinguishing feature is the time domain correlator, which can be described as a wavelet-based matched filter. Just as FM radios perform correlation using long template waveforms (i.e., sine waves), TDSI's correlator uses short templates resembling a damped system's response to an impulse function. This can be employed to optimize the receiver for different bandwidths, or even to optimize characteristic signatures of a specific object. System is also less susceptible to external noise such as that produced by nearby RF transmitters.

The decoupling of the antenna, combined with the compact, planar shape of the antenna and the precise timing control of the pulses allow the creation of "time delay arrays". These arrays have the potential to be electronically scanned allowing three dimensional data collection in a single pass, useful for advanced processing algorithms such as tomographic imaging.

The technique is still in the research phase. TDSI plans to have a van-mounted unit commercially available in the winter of '95, and is hoping to have a man-portable unit completed one year later. Airborne units are in the planning stages but development will be contingent upon funding.

Sensitivity: TDSI has an instantaneous dynamic range of 80 dB, and an effective dynamic range is about 100 dB. These figures are ballpark only based on early research.

Price: Undetermined at this time.

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4.2.3.2. Stepped FM GPR

4.2.3.2.1. Coleman Research Corp.
Lakehurst Dr.
Orlando, FL 32819
Phone: (407) 352-3700
Contact: Bill Steinway x1049

Description

Normally Coleman Research employs COTS equipment to perform their surveys. Their Florida division, however, has been developing a very sophisticated GPR under a contract from the Department of Energy.

Their GPR is a frequency-stepped system (as opposed to a plain pulsed system), which offers several advantages:

- Greater than 91 dB sensitivity
- 5W output power (as compared to mW ratings of pulsed systems)
- Phase-coherent, which improves accuracy linearly rather than in statistical inverse-square law.
- Post-processing algorithms turn unit into a true 3-D synthetic-aperture radar plus other data fusion functions.
- Wide bandwidth which is controllable, yielding higher resolution and easier post-processing.

In the ground-towed configuration, multiple antennas make for wide sweep. They have done preliminary studies for airborne use but have not yet deployed it.

The only unit in existence is still in the R&D phase. Currently they're in the process of tweaking the performance by improving the antennas, which they consider to be close to being finished. There are no current plans for commercialization.

Dr. Steinway legitimized suspicions that most GPR manufacturers calculate their performance in different ways (and express them using incompatible units). According to Steinway, when correctly calculated the SNR of a typical competitor (such as GSSI) would be between 50-70 dB; by comparison theirs is greater than 91 dB. Another interesting fact was that if the power of the GPR were to be increased to 100 watts from the current 5, only 1/2 meter penetration depth would be gained. Instead, future improvements would have come from post-processing in the form of clutter reduction, providing up to 30-40 dB in theoretical improvement.

Sensitivity: 91 dB, no pulse width provided.

Price: Not commercially available, but Dr. Steinway estimated that commercial versions could be sold for $120K.

4.2.3.2.2. FOA

Box 1165
58111 Linköping
SWEDEN
Phone: +46 13 11 8000
Fax: +46 13 131665
Key Contact: Dr. Hans Hellsten

Description

Sweden's National Defense Research Establishment has developed a prototype airborne radar to penetrate foliage and the ground, which could be used by the military for locating surveillance and by civilians for remote sensing. Called the Coherent All Radio Band Sensing (CARABAS) Radar, it is an ultrawide band synthetic-aperture radar (UWBSAR) operating in the 20 to 90 MHz band which employs the stepped-frequency approach to bandwidth expansion.

One unique feature of this system is its node equation approach to wide-band SAR image reconstruction. As opposed to Fourier and associated integral methods for SAR processing, the node equation approach is based on the numerical unfolding of a differential equation along the synthetic-aperture path. So far this is only a theory, as the CARABAS system has yet to show successful field measurements. During previous test flights, an underground pipeline, and an underwater (fresh water lake) cable have been imaged and identified. There is no quantitative test data acquired from a pristine test ground available to date.

Sensitivity and Price: Not available.

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4.2.3.3. Harmonic Radar

4.2.3.3.1. Loral Defense Systems

P.O. Box 85
Litchfield Park, AZ 85340-0085
Phone: (602) 925-7000
FAX: (602) 925-7890
Key Contacts: Jim Haskins
Earl Smith x7788
Tom Craig - Senior Engineer

Description

Jim Haskins of Loral outlined three unique prototypes produced by his division: harmonic radar, foliage-penetrating radar, and a combination of the two that achieve a GPR effect.

The third harmonic radar system operates on the principle that, when probed by a standard radar pulse, only man-made objects will respond with a 3rd harmonic reflection. The radar bounces off junctions from metal objects, but only those which are covered with paint or corrosion. This has the advantages of filtering out the usual sources of GPR clutter (rocks and trees, for example) and narrow down very large parcels for the location of OEW. One prototype of the sensor was built and evaluated by the Army to detect mines from a Huey helicopter. It is probably sitting somewhere in Fort Huachuca, AZ right now as shelfware. They had two different programs, both of which have been completed. No follow-on work has been contracted to date.

The second prototype was a project called INSAR, a foliage-penetrating radar. The project started out with L-band, but moisture in the ground and leaves inhibited its usefulness. They since have switched to UHF frequencies with better results. They were originally thinking of using this to detect illegal drug-growing activity in tree-ridden areas, but the low altitude required for effective readings made the plane an easy target for drug lords. (This work funded by ARPA.)

The third was an offshoot of INSAR: taking the difference between L-band and UHF-band readings of an area and doing some post processing yields effective GPR-like results.

A harmonic SAR system has already been built and used for mine detection applications. It was flight tested in 1991 aboard a helicopter. Surface and subsurface metallic mines were detected in both foliage and clear areas.

Loral is also working on a UHF SAR called MSAR for the study of several phenomena including ground penetration. The radar transmits an 8.8 ms chirp from 500 to 800 MHz. The range swath is limited to 1650 to 1850 m. This radar became operational in the fall of 1993 and is in the process of being tested and calibrated by a team including members of MIT Lincoln Laboratory under ARPA sponsorship.

Sensitivity and Price: No performance specifications were provided, although published papers that might contain such information were promised to be sent via mail. As all items discussed were prototypes, no prices were offered.

4.2.3.4. Interferometric Impulse Radar

4.2.3.4.1. Science Applications International Corp. (SAIC)
McLean, VA
Phone: (703) 821-4300 x4402
IR Technology
Key Contact: Rich Sutton

Description
SAIC is a small consultant house. They do some manufacturing and testing, but fundamentally they're integrators and perform R&D. ·Although they have no products to offer, a few "opportunities" for developing interesting concepts were volunteered.

They've built a truck-mounted GPR with a scanning arm to give 2-D and 3-D effects (although it's only looking one direction down). It boasts of a 6-8 ft. wide trace at 3 miles per hour. Penetrator brand GPRs were used (refer to Section 4.1.3.1.7).

Right now their distinguishing offering is a concept for an interferometric pulse radar, which would construct a 3-D image of what's in the ground by observing from several angles and reinterpreting the resulting interference patterns (not unlike ultrasound or hologram reconstructions).

Sensitivity and Price: Nothing has been built; the 3-D image processing software was just a proposal that they'd like to co-develop with a sponsor.

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4.2.4. Acoustic

4.2.4.1. Army Research Lab (ARL)

Adelphi, MD 20783-1197
Key Contact: John Eicke
Phone: (301) 394-2620.

Description
This division of ARL is involved with acoustic target recognition. They've assembled an inexpensive system that consists of a bank of microphones that can recognize the sound of a tank, jeep, or M-1 from a kilometer down the road. John Eicke feels that the technique in which he specializes cannot be employed for buried OEW detection.

The system works by combining the inputs of several microphones in a process known as "beam forming," which essentially narrows the sensitivity direction and lengthens its reach. The output is then fed to a neural net, a device renown for its ability to do pattern matching and signature recognition. The system is a passive sound identifier only; no imaging occurs.

Sensitivity and Price: Since this technology wasn't viewed as being applicable to OEW detection, this information was not gathered.

4.2.4.2. Imaging

4.2.4.2.2. Tetra Corporation

3701 Hawkins St. NE
Albuquerque, NM 87109-4512
Phone: (505) 345-8623
Fax: (505) 345-7318
Key Contact: William M. Moeny

Description
Tetra makes underwater acoustic sources, "especially sources that are suitable for locating ordnance in the sea." They boast of a technology breakthrough that allows small, light underwater transducers to emanate low-frequency pulses suitable for SONAR probing.

Although the technology hasn't actually been tried yet, Mr. Moeny claims that the 100 Hz to 2 kHz frequency range are ideal for penetrating mud, although details on depth penetration or theoretical water depth were not offered.

The work is being performed for the Navy; other details of its performance were therefore classified.

Sensitivity: As this project is still in the R&D stage, no performance specifications were available.

Price: Unknown, but Mr. Moeny guessed they would cost "a few thousand [dollars] per transducer."

4.2.4.2.1. Dynamic Devices and Systems, Inc.
13025 Beaver Dam Road
Cockeysville, MD 21030
Phone: (410) 744-2424
Key Contact: Brian Hodges

Description

DDS has been in the sonar underwater detection business for many years. Recently they have experimented with applying that technology to underground object detection. As a result of their experimentation, they have developed a solid-state material that can transfer the seismic pulse energy into the ground more efficiently than the usual ceramic materials.

They have proposed to build a functioning system out of this, but have not been awarded the funds to do so. Initial analysis suggests a resolution of +/- 6 inches, and a penetration distance of 75 feet. An array of multiple receivers spaced 1/2 wave apart could allow precise direction calculation, two such arrays allows triangulation to calculate location. Adding more complex receiver arrays and sweep frequencies should allow accurate imaging of the buried device.

Brian Hodges, the company's spokesperson, emphasized that none of this was new technology; it's been used successfully for underwater imaging for many years and should have little difficulty transitioning to other media. They don't plan to do further research unless someone else provides funding.

Sensitivity: Unknown

Price: Unknown, but "not too expensive." An 8x8 array (64-elements) might cost $10K.

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4.2.4.2.3 University of Washington
Applied Physics Lab
Seattle, WA
(206) 543-1300

Description
The Applied Physics Laboratory in the University of Washington / Naval Research Laboratory (APL/NRL) has a 300 kHz sonar lens whose retina is populated with transducers in 8 rows of 16 elements each. Each element forms a conical beam with 1.5 degree resolution between the -3 dB points. The 128 beams span a field of view 48 degrees in azimuth and 12 degrees in elevation. The range resolution can be varied; in one experiment it was set to 10 centimeters. Data from the 128 beams provide a coarse sampling of scattering density as a function of range, elevation, and bearing.

The fluid placed in the lens cavity must be carefully selected to keep the lens in focus over changing water temperatures. They're using a fluid that maintains focus over a temperature range of about 13 degrees Celsius. Data is both recorded within the lens unit and sent topside to a PC-based real-time display.

Sensitivity and Price: Not available.

4.2.5. Visible Imaging

4.2.5.1. Jet Propulsion Laboratory (JPL)

4800 Oak Grove Dr.
Pasadena, CA 91109
Phone: (818) 354-4321
Key Contact: Clayton LaBaw

JPL is exploring the active pixel sensor fabricated in standard foundry CMOS technology. A 40x40 micron pixel configured in a 28x28 array has been designed and demonstrated. The image sensor was operated at a pixel rate of approximately 0.5 megapixel/sec. The charge to voltage conversion rate was estimated to be 4.0 microvolt/electron with a saturation level for this surface-channel device of approximately 600 millivolts. Fixed pattern noise was observed to be approximately 1.5% full-scale and can likely be reduced by an order of magnitude by improved on-chip signal processing. While this device used destructive readout with a floating diffusion sense amplifier, a non-destructive floating-gate sense amplifier has also been demonstrated.

Further efforts using standard CMOS are aimed at demonstrating a "camera-on-a-chip" for use in future microspacecraft applications. The camera-on-a-chip will include an on-chip A/D converter to allow a full digital interface with external circuitry.

Sensitivity and Price: No conventional sensitivity readings are available. The project is still in the research phase.

4.2.6. Infrared Imaging Spectrometry

4.2.6.1. Jet Propulsion Laboratory (JPL)

4800 Oak Grove Dr.
Pasadena, CA 91109
Phone: (818) 354-4321
Key Contact: Clayton LaBaw

TIRIS - Thermal IR Imaging Spectrometer

Instrumentation with the ability to provide airborne imaging spectrometry in the thermal infrared wavelength region is being developed at JPL under a grant from the University of Oklahoma Health Sciences Center. The Thermal InfraRed Imaging Spectrometer (TIRIS) will feature operation from 7.5 to 14.0 μm with uncooled optics and as a result of advanced detector/filter utilization techniques.

Specifications: and has been designed to provide the following capabilities:

Swath width	200 m
Ground resolution	10 m
Spectral resolution	100 nm
Spectral channels	64
Spectral coverage	7.5 to 14.0 μm

The TIRIS swath lengths are determined by time on flight line.

Price: Although not for sale, the TIRIS is available for any qualified user from JPL. It is normally deployed in a NASA C-130 aircraft.

4.2.7. LIDAR

NOTE: Numerous other companies, in addition to the ones listed below, are currently involved in 3-D LIDAR (or LADAR) development, information on which is not currently available. A partial list follows:

- Loral Vought Systems Corp.
- Air Force Wright Laboratory, Solid State Electronics Directorate, Electro-Optics Division
- Los Alamos National Laboratory
- Hughes Aircraft, Electro-Optical and Data Systems Group
- General Dynamics, Convair Division
- NASA Goddard Space Flight Center

4.2.7.1. Army Research Lab (ARL)

Adelphi, MD 20783-1197
Phone: (301) 394-3130
Key Contact: Dr. Zoltan Sztankay

ARL is developing a 3-D LADAR system designed to identify military targets on the ground. The system uses both time modulation for range as well as standard LIDAR reflectance to gain its extra dimension. Other ARL divisions specialize in taking the LADAR's output and performing automated target recognition.

Dr. Sztankay speculated that such a LADAR system could be successfully employed to find OEW on the surface. Normally an airborne LADAR system is impractical for battlefield scanning because of the amount of time required for the scan, but for ordnance detection there's no time pressure and therefore might be practical.

Sensitivity: Not currently measured by developers.

Price: The product is still in the R&D phase, but a ballpark estimate for price was around $100K for short range, and millions of dollars for long-range airborne. (Development costs not included in estimate.)

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4.2.7.2. CNR Istituto di Èlettronica Quantistica
50127 Firenze
Italy
Phone: (011) +39 55 301422

Description
This Italian research team has performed line spectra research to evaluate the ability of LIDAR in detecting thin oil films on natural waters. Oil film thicknesses as little as 0.01 μm were detected.

For more information about this research, refer to Applied Optics magazine, Vol. 22 no. 1 January, 1983, pg. 48-53.

4.2.7.3. Schwartz Electro-Optics
Orlando Sensor Division
Research Division
45 Winthrop Street
Concord, MA 01742
Key Contact: Dr. Peter Moulton, Dr. Glen A. Rines (Laser Physicist)
Phone: (508) 371-2299
Fax: (508) 371-1265
Sales: Sidney Wright (407) 298-1802

Description
The research division of Schwartz Electro-Optics has been developing LIDAR components for the Air Force and for NASA, although they have yet to construct an entire system.

Their LIDAR components are aimed at air pollution measurement. Using a technique called differential absorption LIDAR, two light frequencies are exposed to the airborne pollutants and the spectral response from them is measured and identified based on fingerprints. Using this technique, one can map a gas concentration over a wide area.

Dr. Moulton thinks that LIDAR may be ill-suited for the detection of buried OEW, unless the chemicals within the ordnance excrete a known gas into the air, or if residue chemicals on the surface fluoresce in the presence of LIDAR wavelengths.

Sensitivity: Unknown, but in the parts per million (ppm) range.

Price: Can vary between $50-500K, depending on range, specifics, and how sophisticated the requirements are.

4.2.7.4. Waterways Experimental Station (WES)
Coastal Engineering Research Center Lab
3909 Halls Ferry Road
Vicksburg, MS 39180
WES Main number: (601) 636-3111
Key Contact: Joan Pope - Task Manager
Phone: (601) 634-3034

Description
Ms. Pope has been investigating many different types of sensors to detect OEW on the bottom of lake beds, including magnetometers, side-scan sonar, GPR, and EM (specially adapted for underwater use). She is trying to create a conceptual model of the distribution and movement patterns of the OEW over time.

For the past five years, her division has also been developing a new helicopter-borne scanning LIDAR mapping system called SHOALS (which stands for Scanning Hydrographic Operational Airborne LIDAR Surveying System) for bathymetry purposes (which means for mapping the lake bed bottom). Currently in the research stage, the system was built for them by OPTECH (Refer to Section 4.2.1.5.2) and is now being field-tested to make sure the laser mapping aspects work to specification, and that their software processing is accurate. Although it's not an imaging system, they are considering fusing its output with additional multi-spectral imaging sensors in the future.

The SHOALS system has been "performing beautifully" during its initial field tests, but even so there are a list of improvements being readied for the next iteration.

Sensitivity and Price: No performance details were offered. The system has so far cost between $9-10M over a five-year period.

4.2.8. Nuclear Technology

This technology can theoretically be employed for buried OEW detection. Since the vast majority of nuclear technology vendors target their systems toward airport security and other close proximity searches, only those products that might lend themselves toward remote OEW detection are listed here.

4.2.8.1. Applied Research Associates (ARA)
Albuquerque, NM
Phone: (505) 881-8074
Key contacts: Jim Eddings
Huntsville Division: Jim Boschma
Phone: (205) 882-9394.

Description
ARA specializes in spatial risk assessment, and environmental site characterization.

One of their ideas for future prospective projects is to employ gamma activation (similar to neutron activation) for the detection of encased high explosives. Such a technique would be good for "avoiding the negative" identification: if it's not explosive, don't spend the money and time to dig it up. A gamma radiation device can also neutralize dangerous chemicals (anything with a loose oxygen bond, like nerve gas agents) given enough strength.

(For more information on ARA, refer to Section 4.1.4.1.)

Sensitivity and Price: The idea is in the concept stage only. No further information is available.

4.2.8.2. Ballena Systems Corp.
5820 Stoneridge Mall Rd. Suite 205
Pleasanton, CA 94588
Phone: (510) 460-3740
Contact: Dr. Kendall Casey
Fax: (510) 460-3751.

Description
Ballena has proposed studying the use of neutron-activation methods for the detection of chemical surety material (CSM). To date, they have not developed any technology to do so.

(Refer to Section 4.1.10.1 for a more complete description of Ballena.)

4.2.8.3 Jet Propulsion Laboratory

4800 Oak Grove Dr.
M/S 183-806
Pasadena, CA 91109
Contact: Dr. Ara Chutjian
Phone: (818) 354-7012

JPL has developed a trace-species detection system which is currently being adapted as an explosives-vapor detector for use at airports. The system works by drawing in air from around the area in question and passing it over a sensitive surface which adsorbs the heavier molecules such as those found in explosives. The instrument employs a technique called READ (Reversal Electron Attachment Detection), which works by attaching zero-velocity electrons to the heavy molecules from the air sample (ionization). The resulting negative ions are extracted and mass analyzed.

The system has highest sensitivity for molecules which have a large attachment probability for thermal electrons. These include explosives (such as EGDN, TNT, PETN, and RDX), CFC's, nerve gases, and many others. System sensitivities to selected elements are conservatively stated to be 10 parts per trillion.

The system can be adapted to soil use, specifically for the detection of UXO by detecting explosive contents from broken or corroded casings that have leached into the soil. The system is currently undergoing airborne sensitivity testing.

Sensitivity: For the above-mentioned chemical explosive molecules, sensitivity is measured in the parts-per-trillion level.

Price: An van-deployable unit is being developed for the FAA. Current estimated costs of this system are approximately $150K, excluding labor.

4.2.8.4. Quantum Design/Quantum Magnetics Corp.
11578 Sorrento Valley Road Suite 30
San Diego, CA 92121
Phone: (619) 481-4400
Key Contact: Dr. Bill Avrin

(Quantum Design also makes optically pumped and SQUID magnetometers and an advanced EM sensor. For more information refer to Sections 4.2.1.1.1, 4.2.1.2.7 and 4.2.2.3.1.)

Description
Quantum is actually two separate companies; both of which deal primarily in SQUID technology.

They are considering the use of Nuclear Magnetic Resonance (NMR) technology to distinguish chemical fingerprints of ordnance below the surface (even if completely encased). Because it would take several seconds to perform the identification, the most likely usage scenario would be to detect the presence of something using conventional magnetometer techniques, and then employ the NMR system to identify objects in areas that require further investigation. (It's also an ideal technology for screening luggage for non-metallic bombs at airports.)

Price and Sensitivity: The idea is in the concept stage only. No further information is available.

4.2.8.5. Thermetics Detection Inc.
Cambridge, MA
Phone: (508) 251-2000
Key Contact: Barley Dutton

Description
Thermetics Detection deals with bomb and plastic explosives detection equipment. They make a trunk-carriable unit that can detect trace quantities of explosive chemicals down to ppm range.

4.2.9 Multi-Sensor Platforms

4.2.9.1. Battelle

505 King Ave.
Columbus, OH 43201
Key Contact: Dr. Keith Shubert
Phone (614) 424-4916

(Battelle is also working on an Airborne GPR. Refer to Section 4.2.3.1.2 for more details.)

Description
Battelle is developing a Remote Characterization System (RCS) in conjunction with the Pacific Northwest Laboratories, Oak Ridge National Laboratory, Lawrence Livermore National Laboratory, Idaho National Engineering Laboratory, and Sandia National Laboratories. RCS is a remotely operated vehicle for characterizing and locating buried waste in an open-air environment. The RCS has a GPR, flux-gate and cesium-based magnetometers, an EM31 ground-conductivity sensor, a chemical detector, and a gamma radiation detector on board, plus a global positioning satellite (GPS) system for accurate positional logging.

Sensitivity and Price: As the devices are still in the research stage, no information is available.

4.2.9.2. Nichols Research Corporation (NRC)

4040 S.W. Memorial Parkway
Box 400002
Huntsville, AL 35802
Phone: (205) 883-1140
Fax: (205) 882-3422
Key Contacts: Pete Gray - head of corporate development
Al Boyer x1300
Scott Kordella (703) 893-9720 (RF Fence)

Description
NRC is a general R&D center for NASA, AT&T, and all branches of the military. They are a systems engineering technical assistance contractor and specialize in front-end analysis of sensor-related technologies, data fusion, and discrimination. They have experience with IR, RF, GPR, electro-optic, laser, and advanced optical sensors.

They have applied expert systems and neural networks to sensor data, which is useful in detecting oil spills. They also feel their oil spill techniques (essentially GPR post-processing) could be applied to OEW detection.

Nichols has proposed integrating several commercial, off-the-shelf (COTS) technologies to enhance performance for the Corp.'s specific needs, although they haven't actually built anything. One proposed system would integrate a COTS magnetometer with a global positioning system (GPS) receiver for faster and more accurate ground surveys. Another similar proposal would combine an available GPR with GPS. Mr. Boyer didn't mention which COTS products would be integrated into these faster-to-use systems.

A third proposal (not submitted to the Corps of Engineers) was particularly intriguing. Three low-frequency radars would be placed at reasonable distances at each other and pointed at the ground; fusing the three readings afterwards (a process called geotomography) could yield higher resolution images at deeper penetration depths than any of the single radars could have provided. This concept was called the "RF Fence" and was designed to track and identify underground leakages.

Specifications: No performance specs were available for any of the three proposals.

Price: No prices were available for any of the three proposals.

4.2.9.3. Science Applications International Corp. (SAIC)
2950 Patrick Henry Dr.
Santa Clara, CA 95054
Phone:(408) 727-0607
FAX: (408) 727-8748
Contact: Dr. Joseph Bendahan

SAIC is a DoD contractor that primarily performs software development, R&D, and the constructs one-of-a-kind instruments. They have proposed (but not fabricated) the development of a multi-sensor ground-based platform for locating OEW, specifically land mines. Sensors incorporated include magnetometers, GPR, and a TNA nuclear sensor for discriminating between explosives and chemical weapons. The proposed platform would have an on-board expert system capable of mission planning, data acquisition and processing, and mapping accurate to within 10 cm.

The platform would be an all-terrain, teleoperated, unmanned ground vehicle that minimizes operational risks to human health. Of the three sensor types proposed, only the nuclear device was developed in-house. (The magnetometer is an off-the-shelf optically pumped unit made by GEM Systems, Inc., and the GPR is based on the pulseEKKO 1000 commercial unit from Sensors and Software, Inc.) The nuclear device is a thermal neutron analysis (TNA) type, designed to detect the chemicals within the plastic-cased land mines.

SAIC only develops products, and does not sell them.

Sensitivity: The platform has not been constructed, and it is difficult to measure combined sensitivity before data fusion techniques are applied. (Refer to the Sensors and Software Inc. entry, Section 4.1.3.1.9, for the GPR sensitivity, and to GEM Systems (Section 4.1.1.2.2) for the magnetometer sensitivity.)

Price: Not applicable.

4.2.10. Other Related Technologies

Although none of the technologies listed in this section can be classified as a sensor, they do provide significant advancements in other aspects of sensor data collection that would allow the extraction of more information when used with conventional sensors.

4.2.10.1. Areté Engineering Technologies Corp. (AETC)
1725 Jefferson Davis Highway Suite 707
Arlington, VA 22202
Phone: (703) 413-0500
FAX: (703) 413-0505 .
Key Contact: Dr. Tom Bell

Areté Engineering Technologies Corp. is a recent spinoff from Areté Associates, which has been a defense contractor since 1976. Their goal is to adapt advanced remote sensing technologies to quantitative environmental surveying.

AETC has developed sophisticated classification processing algorithms for existing magnetometers and electromagnetic induction sensors. The procedure is to bury ordnance of known size and type at a known depth and then measure it with the instrument whose readings are to be enhanced. The output is then available for pattern matching when the same instrument is investigating a site with unknown buried OEW. By referring to these previously generated physics-validated models of sensor response to any particular UXO or number of UXO at various depths, they are able to confirm the presence or absence to any required level of confidence for UXO buried down to about ten feet.

Currently, the two instruments supported are the Schonstedt GA-72 magnetometer, and the Geonics EM31 and EM38 electromagnetic induction sensors.. There are currently negotiating with the Naval Research Lab to merge these two sensors and perform data fusion on their output. They predict that with the combined sensors they could locate even non-magnetic objects, estimate their size and number, and specify the depth at which UXO can be found.

AETC also sells a general-purpose data logging system called Geodaps. The product takes instrument readings via an RS-232 serial port and combines it with a differential GPS output plus accurate time stamp, and radios the stamped data packet to a base computer via a radio link. (The differential GPS takes reading from both the satellite and a second transmitter placed at a known location and communicating with the GPS satellite as well. Using this extra transmitter, all intentional inaccuracies in the civilian GPS channel are eliminated, and accuracy is good to 20 cm.) This system was employed at the Spring Valley remediation site.

Sensitivity: Sensitivity is a characteristic of the sensor employed; their technology allows greater accuracy in classification in size and location. Over a range of sizes from a few inches to a few feet, they can give size estimates to within 10-15% for depths ranging from "shallow" to 10 feet deep.

Price: Post-processing software is not commercially available, although they are currently working with Geometrics to make commercially available software to sell with Geometrics' instruments.

4.2.10.2. Ballena Systems Corp.
5820 Stoneridge Mall Rd. Suite 205
Pleasanton, CA 94588
Phone: (510) 460-3740
Contact: Dr. Kendall Casey
Fax: (510) 460-3751.

Description

Ballena is working on advanced, wavelet-based signal processing techniques for magnetometer sensor data to help isolate the OEW from subsurface clutter. The processing algorithms would also allow for an estimation of object depth from OEW signatures.

They are also working on sensor fusion techniques to mathematically combine the outputs of sensors that exploit different physical phenomena.

(Refer to Section 4.1.10.1 for a complete description of Ballena.)

4.2.10.3. Oak Ridge National Laboratory
Oak Ridge, TN
Phone: (615) 576-5454
Key contact: Joe B. Dooley (615) 576-1861 direct

Oak Ridge has developed a signal processing technique that provides improved visualization of target geometry and other properties. The signal processing technique can be used to enhance many geophysical measurements received from sensors such as GPR, seismic, and electromagnetic induction.

4.2.10.4. PRC

[Address unlocatable; Representative spoke at May, 1994 UXO conference]
Key Contact: Sid Owen

Description

PRC is creating a software system called SIDCAPS to provide real-time processing of multiple sensor data and generate status and navigation information. The system design effort is currently in progress and was planned to be complete in April 1994.

They are also developing an Ordnance Detection Expert Support Application (ODESA) expert system for identification of buried ordnance. The approach is to use a combination of COTS expert system shells, artificial neural network systems, probabilistic casual models, genetic algorithms and fuzzy logic systems. A real-time system is not planned.

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4.3. SENSOR PRODUCT SUMMARY TABLES

This section provides a summary (in tabular form) of all products and vendors reviewed in this document for each sensor category: magnetometers, electromagnetic (EM) sensors, GPR, seismic sensors, IR sensors, MMW, visible imaging, LIDAR, and nuclear technology. Notice that products from both "State-of-the-Art" and "Emerging Technologies" sections appear in these tables to provide the reader with a single starting point for finding more information on companies and comparing their performance.

Each table listing contains the company name, product type, first-order performance specifications (provided for initial comparison purposes only), and a section number where more detailed information can be found.

The following tables appear in this section:

4.3.1. Magnetometers Summary Information Table

Table 4.3.1 summarizes the magnetometer products as discussed in Sections 4.1.1 and 4.2.1.

Table 4.3.1 Magnetometers: Product Type vs. Company name

Product Type	Vendor	Model Name or Number	Sensitivity (gamma)	Price	Refer to Section for Detailed Info
Proton Precession Magnetometer	Geometrics	G-856AX G-865AG (Gradiometer)	0.1 Grad: 0.03 gamma/foot	$5K Gradiometer kit: $1.6K	4.1.1.1.2
Proton Precession Overhauser Effect Magnetometer	GEM Systems	(none)	0.01	$9K; $12K for Gradiometer	4.1.1.1.1
Proton Precession Magnetometer	Scintrex	ENVIMAG	0.1	$5K	4.1.1.1.3
Optically Pumped Cesium Magnetometer	Geonex Aerodat	(none)	0.05	Only sell survey service	4.1.1.2.4
Optically Pumped Cesium Gradiometer	Geonex Aerodat	(none)	0.01 nT/m	Only sell survey service	4.1.1.2.4
Optically Pumped Cesium Magnetometer	Geometrics	822 (Cesium) 833 (Helium) 858 (Next Generation Dec. '94)	C: 0.01 nT at 0.1 nT resolution; H: 0.01 nT at 0.01 nT resolution	$14.5K (C) $17.5K (H)	4.1.1.2.3
Optically Pumped Potassium Magnetometer	GEM Systems	GSMP-20	0.01 pT (more sensitive at lower rates)	$25K Gradiometer: $45K	4.1.1.2.2
Optically Pumped Cesium Magnetometer	Scintrex	"Smart Mag"	0.01 nT	$13K - $18K	4.1.1.2.5
Optically Pumped Cesium Magnetometer	ADI	TM-4	0.01 (Cesium) 0.005 (Helium)	$30K ($100K for complete system)	4.1.1.2.1
Optically Pumped Magnetometer	Varian Associates	Mk22 (aka V92)	1.0	(Now offered by Scintrex)	4.1.1.2.7
Dead-Zone-Free Optically Pumped Magnetometer	Quantum Design	(none)	still in research	still in research	4.2.1.1.1
Fluxgate Gradiometer	Schonstedt	GA72CV	(probably bet. 0.5 and 0.1 Gamma)	$850.00	4.1.1.3.6
Fluxgate magnetometer	Geo-Centers	STOLS	0.1 nT	Surveying services $2K per acre.	4.1.1.3.4
Fluxgate Magnetometers	Bison	(Russian)	2.0	$1.5K	4.1.1.3.2.
Fluxgate Magnetometer	Foerster Instruments	FEREX 4.021	8.9 cm shell at 3 m depth	$17.3K	4.1.1.3.3

Product Type	Vendor	Model Name or Number	Sensitivity (gamma)	Price	Refer to Section for Detailed Info
Fluxgate Magnetometer	Applied Physics Systems	APS 428C	1 μGauss to 2 Gauss range; noise to 3 x 10^{-7} Gauss RMS/√Hz	\$3K	4.1.1.3.1
Fluxgate Gradiometer (Wheelbarrow)	Sage Earth Science (EG&G Idaho)	(none)	0.1 nT/m; 100 Hz rate	"Around \$5K"	4.1.1.3.5
Fluxgate short-baseline magnetometer	CSS	(none)	0.1 nT/ft.	\$75K	4.2.1.3.2
3-Axis Fluxgate Magnetometer	CSS	(none)	0.001 nT/ft.	not commercially available	4.2.1.3.2
3-Axis Fluxgate Magnetometer	Applied Physics Systems	APS 520(A)	1 μGauss to 2 Gauss range; noise to 3 x 10^{-7} Gauss RMS/√Hz	\$5K - \$7K	4.1.1.3.1
3-Axis Fluxgate Magnetometer	Applied Physics Systems	APS 533	1 μGauss to 1 Gauss range; noise to 10^{-6} Gauss RMS/√Hz	\$2K-\$3K each	4.2.1.3.1
Fiber-optic Magnetometer	Optech	(none)	1.0	still a prototype	4.2.1.5.2
Underwater 3-axis fiber-optic vector magnetometer	Naval Research Lab	(none)	(not given; probably 0.1 nT)	\$20-30K for each 3-axis sensor	4.2.1.5.1
SQUID Components	Quantum Design	(none)	5 $\mu Ø_o$/√Hz	\$10K per channel	4.2.1.2.7
Superconducting Rock Magnetometer	2G Enterprises	(none)	4 x 10^{-9} EMU RMS √Hz for 4.2 cm access	\$115K for 3-axis system	4.2.1.2.1
SQUID Components	Conductus	77K 4K	(not given)	77K: \$4K 4K: \$1.5K	4.2.1.2.4
RF SQUID	FIT (Germany)	HS20 HS07	$2x10^{-3}$ nt/√Hz $0.7x10^{-3}$ nt/√Hz	DM 1,500 DM 5,000	4.2.1.2.5
DC SQUID	CSS	(none)	10^{-3} nT/ft.	\$500K-\$1M	4.2.1.2.3
Room-temperature SQUID	Loral	(none)	classified	\$750K - \$860K	4.2.1.2.6
SQUID components	Applied Physics Systems	(none)	5 x 10^{-6} Φ_o/√Hz	\$11K	4.2.1.2.2

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Product Type	Vendor	Model Name or Number	Sensitivity (gamma)	Price	Refer to Section for Detailed Info
Electron Tunneling Magnetometer	JPL	(none)	0.001 gamma	$5.00 in quantity	4.2.1.4.1

4.3.2. Electromagnetic Induction Sensors Summary Information Table

Table 4.3.2 summarizes the EM induction sensor products as discussed in Sections 4.1.2 and 4.2.2.

Table 4.3.2 Electromagnetic Induction Sensors: Product Type vs. Company Name

Product Type	Vendor	Model Number or Name	Sensitivity	Price	Refer to Section for Detailed Info
Ground Towed EM Induction Sensor	Pylon/Naeco Asso. Inc.	VMOD	(Nothing comparable provided)	$63K	4.1.2.3
Helicopter EM Sensor	Geonex Aerodat	(none)	< 1 ppm; <60 dB	$12K per day for site survey	4.1.2.1
EM Induction Sensor	Geonics Ltd.	EM61 EM38 EM31	8 nV/m2 5x10-5 5x10-5	$12K $7K $14K	4.1.2.2
AC Susceptibility EM Sensor	Quantum Design	(none)	500 lb. bomb detected at 15 m (predicted)	Similar systems for $100K.	4.2.2.3.1
EM Sensor	University of Arizona	LASI High-Resolution Ellipticity System	0.1% location accuracy	n/a	4.2.2.2

4.3.3. Ground-Penetrating Radar Summary Information Table

Table 4.3.3 summarizes the GPR sensor products as listed in Sections 4.1.3 and 4.2.3.

Table 4.3.3 Ground-Penetrating Radar: Product Type vs. Company Name

Product Type	Vendor	Model Number or Name	Sensitivity	Price	Refer to Section for Detailed Info
Side-Scan Radar/ Underwater	AUSS	(none)	n/a	n/a	4.1.3.1.1
Land-Based GPR	GSSI	SIR3, SIR10	SIR10: 160 dB	SIR3: $18K SIR10: $40K (w/o antenna)	4.1.3.1.3
Stepped FM GPR	GeoRadar, Inc.	(none)	96 dB	$25K	4.1.3.1.4
Land-Based GPR	Geoscience	RAMAC Borehole Radar + GPR	nothing provided	$250K for RAMAC; $40K for GPR	4.1.3.1.5
Ground-based UWB Radar	LLNL	(none)	nothing comparable	n/a	4.1.3.1.6
Highway and mine Land-Based GPR	Penetrator	(none)	3" spatial resolution when <1m from ground	$60K - $200K depending	4.1.3.1.7
Land-Based GPR	Pulse Radars, Inc.	(none)	nothing comparable	$75K-80K	4.1.3.1.8
Land-Based GPR	Sensors & Software, Inc.	pulseEKKO IV & 1000	IV: 155 dB 1000: 133 dB	$32K USD (both)	4.1.3.1.9
Airborne GPR	AES	EMS-20 EMS-5	160 dB (not listed)	$50K/day to perform survey	4.1.3.2.1
Airborne GPR	ERIM	RAIL-SAR	can image two buried barrels under 1m of soil	research phase	4.1.3.2.2
Airborne SAR	JPL	(none)	-30 to -50 dB	NASA DC-8 can be scheduled	4.1.3.2.3
Airborne SAR UWB GPR	SRI	Full-Pen 1&2	-40 dB/m^2	Only sell survey service	4.1.3.2.5, 4.1.3.2.4
UWB Radar	Army Research Lab	(none)	SNR= 10dB	n/a	4.2.3.1.1

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Product Type	Vendor	Model Number or Name	Sensitivity	Price	Refer to Section for Detailed Info
Airborne GPR	Battelle / Ohio State	(none)	Goal is detecting small ordnance to 1m.	[research phase]	4.2.3.1.2, 4.2.3.1.5
Ground-Based Imaging GPR	Mirage Systems	(none)	not offered	Unit under constructio n	4.2.3.1.3
Airborne UWB SAR	MIT Lincoln Lab	"Steel Crater"	n/a	n/a	4.2.3.1.4
UWB Correlator Receiver Radar	Time Domain Systems Inc.	(none)	80 dB (100 dB effective)	research phase	4.2.3.1.6
Stepped FM GPR	Coleman Research	(none)	91 dB	$120K (est'd; still in research phase)	4.2.3.2.1
Stepped UWB SAR	FOA (CARABAS)	(none)	n/a	n/a	4.2.3.2.2
Harmonic Radar	Loral	(none)	n/a	n/a	4.2.3.3.1
Interferometric Impulse Radar	Science Applications International	(none)	nothing built	just a proposal	4.2.3.4.1

4.3.4. Cone Penetrometers Summary Information Table

Table 4.3.4 summarizes the partial cone penetrometer products list as they appear in Section 4.1.4. (Refer to Section 4.1.4 for an explanation as to why this list is incomplete.)

Table 4.3.4 Cone Penetrometer - Product Type vs. Company Name

Vendor	Price	Model Number or Name	Sensitivity	Refer to Section for detailed information
Applied Research Associates (ARA)	N/A	(none)	Can "see" up to 3m in depth	4.1.4.1
Earth Tech Corp.	$50-120/hr; $6.75/ft.	(none)	(none offered)	4.1.4.2
Stratigraphics	About. $175/hr; $6/ft.	(none)	(none offered)	4.1.4.3

4.3.5. Visible Imaging Summary Information Table

Table 4.3.5 summarizes the visible imaging sensor products as listed in Sections 4.1.5 and 4.2.5.

Table 4.3.5 Visible Imaging - Product Type vs. Company Name

Product Type	Vendor	Model Number or Name	Spatial and Spectral Resolution	Price	Refer to Section for Detailed Info
Multi-spectral imaging	ERIM	(none)	not available	not available	4.1.5.1
Airborne Imaging Spectrometer	JPL	AVIRIS	30 m, 10 nm	[NASA Resource]	4.1.5.2, 4.2.5.1

4.3.6. IR Sensors Summary Information Table

Table 4.3.6 summarizes the infrared sensor products as listed in Sections 4.1.6 and 4.2.6.

Table 4.3.6 Infrared Sensors - Product Type vs. Company Name

Product Type	Vendor	Model Number or Name	Sensitivity	Price	Refer to Section for Detailed Info
8-12 micron IR Sensor	Bales Scientific	(none)	0.05 C	$60K	4.1.6.5
IR Radiometric	Inframetrics	760	0.1 C	$49K - $60K	4.1.6.9
3-5 micron Near IR camera	Army Research Lab	(none)	not available	not available	4.1.6.4
IR Imaging	Amber	AE-4128, Radiance	5.5 µm sensitivity; detectivity = 4×10^{11} $cmHz^{1/2}/W$.	AE-4128: $40K Radiance: $80K	4.1.6.2
Mid-wave IR sensor	Cincinnati Electronics	IRC-160ST, IRRIS-160ST IRRIS-256ST TVS-2500	0.03C 0.025C 0.02C 0.1C	$39.5K $46.9K $85.7K $48.3K	4.1.6.6
Thermal Imager	Dorex	DITI-256	0.07 C	$85K	4.1.6.7
Dual-band IR scanner	Agema	210 880 900 1000	0.05° C 0.05° C 0.07° C 0.1 ° C (All NEΔT)	$19.5K $55K $85K-115K $98K	4.1.6.1
Spectro-radiometer	Analytical Spectral Devices	—	1.9×10^{-6} $Watts/cm^2/nm/steradian$ at 1700 nm	$25K - $60K	4.1.6.3
multi-channel IR scanners	Geophysical & Environmental Research		nothing further available	nothing further available	4.1.6.8
Spectro-radiometer	Optronic Labs	-	"sensor not applicable"	"sensor not applicable"	4.1.6.12
Airborne Image Spectrometer	JPL	AVIRIS	30 m, 10 nm	[NASA Resource]	4.1.6.10, 4.2.6.1

4.3.7. MMW Radiometry Summary Information Table

Table 4.3.7 summarizes the millimeter wave radiometry sensor products as listed in Sections 4.1.7.

Table 4.3.7 MMW Radiometry - Product Type vs. Company Name

Product Type	Vendor	Model Number or Name	Sensitivity	Price	Refer to Section for Detailed Info
MMW Radar	Army Research Lab	(none)	unknown	unknown	4.1.7.1

4.3.8. LIDAR (2-D and 3-D) Summary Information Table

Table 4.3.8 summarizes the LIDAR sensor products as listed in Sections 4.1.8 and 4.2.7.

Table 4.3.8 LIDAR - Product Type vs. Company Name

Product Type	Vendor	Model Number or Name	Sensitivity	Price	Refer to Section for Detailed Info
LIDAR	Schwartz Electro-Optics	(none)	in the ppm range	$50K - $500K	4.2.7.3
2-D LIDAR	Kaman Aerospace	Magic Lantern / FishEye	no standard metric	$250K	4.1.8.1.1
Polarimetric LIDAR	Waterways Experimental Station	REMIDS	3 inch square from 200 ft.	$750K if commercially available	4.1.8.1.2
LIDAR Mapping	Waterways Experimental Station	SHOALS	still in research	So far $10M over 5 years	4.2.7.4
3-D LADAR	Army Research Lab	(none)	not currently measured	$100K est'd (still in research)	4.2.7.1
Line-Spectra LIDAR	CNR Instituto di Elettronica Quantistica	(none)	0.01 µm	still in research	4.2.7.2

4.3.9. Nuclear Technology Sensors Summary Information Table

Table 4.3.9 summarizes the nuclear sensor products as listed in Sections 4.2.8.

Table 4.3.9 Nuclear Technology - Product Type vs. Company Name

Product Type	Vendor	Model Number or Name	Sensitivity	Price	Refer to Section for Detailed Info
NMR	Quantum Design	(none)	proposal	proposal	4.2.8.4
gamma activation of high explosives	ARA	(none)	proposal	proposal	4.2.8.1
Neutron Activation	Ballena	(none)	proposal	proposal	4.2.8.2
Trace-Species Detection System	Jet Propulsion Laboratory	(none)	parts-per-trillion level	$150K + labor	4.2.8.3
Bomb Detection	Thermetics Detection	(none)	not available	not available	4.2.8.5

4.3.10. Acoustic Sensors Summary Information Table

Table 4.3.10 summarizes the Acoustic sensor products as listed in Sections 4.1.4 and 4.2.4.

Table 4.3.10 Acoustic Sensors - Product Type vs. Company Name

Product Type	Vendor	Model Number or Name	Sensitivity	Price	Refer to Section for Detailed Info
Cone Penetrometer	Applied Research Associates	n/a	can "see" up to 3 meter radius	not provided	4.1.4.1
Cone Penetrometer Testing Service	Earth Tech Corp.	n/a	not provided	avg. base $200/hr + other fees	4.1.4.2
Cone Penetrometer Testing Service	Strati-graphics	n/a	not provided	$175/hr + other fees	4.1.4.3
Acoustic Object Identifier	Army Research Lab	(none)	n/a	n/a	4.2.4.1
Underwater Acoustic Sensors	Tetra Corp.	(none)	not available	"A few $K per transducer"	4.2.4.2.1
Underwater Sonar	Dynamic Devices and Systems	(none)	proposal	proposal	4.2.4.2.2

4.3.11 Multi-Sensor Platform Summary Information Table

Table 4.3.11 summarizes the multiple-sensor platforms listed in Sections 4.1.9 and 4.2.9.

Table 4.3.11 Multi-platform Sensors - Product Type vs. Company Name

Vendor	Technologies	Model Number or Name	Sensitivity	Price	Refer to Section for Detailed Info
Army Research Lab (ARL)	Infrared MMW UWB Radar Acoustic Sensors LIDAR	n/a	(see individual descriptions)	(see individual descriptions)	4.1.6.4 4.1.7.1 4.2.3.1.1 4.2.4.1 4.2.7.1
Battelle Inc.	GPR, magnetometers, ground conductivity, chemical, gamma radiation.	n/a	(not constructed)	(not constructed)	4.2.9.1
Nichols Research Corp.	IF, RF, GPR	(not constructed)	(not constructed)	(not constructed)	4.2.9.2
Science Applications International Corp.	GPR, Magnetometer, TNA	Ordnance Detection System (ODS)	not yet determined	n/a	4.2.9.3

4.3.12. Other Related Technologies Summary Information Table

Table 4.3.12 summarizes the "Other Related Technologies" listed in Sections 4.1.10 and 4.2.10.

Table 4.3.12 Other Related Technologies Summary

Vendor	Product Type	Refer to Section for Detailed Info
Areté Engineering Technologies Corp. (AETC)	Post-Processing Software for Enhanced Classification	4.2.10.1
Ballena Systems Corp.	Advanced Data Analysis	4.1.10.1, 4.2.10.2
Chemrad Tennessee Corp.	Data Logging Device	4.1.10.2
Dean Consulting and Research	EM and Impulse Radar Expertise	4.1.10.3
Oak Ridge National Laboratory	Signal Processing Software	4.2.10.3
PRC	Data Fusion Software	4.2.10.4

4.3.13. Tally of Sensor Technology Popularity

Table 4.3.13. presents the number of vendors that offer products in each technology category covered in this report. In addition, the average applicability scores as computed from entries in Tables 3.5.1 through 3.5.3 also appear for comparison.

Each of the entries are ranked visually. Icons are defined below each table. The meanings of the definitions appear below:

● **Most Applicable** - under the given conditions, these technologies will provide the best performance in their respective areas.

◒ **Average** - this technology will work adequately under the stated conditions, although there are other technologies reviewed herein that will perform the job faster, with greater sensitivity, from greater distances, or with fewer false alarms.

○ **Poor** - under the stated conditions, this technology is not recommended to be used for the detection and location of OEW.

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Table 4.3.13 Tally of Number of Manufacturers for each Sensor Technology

Sensor Type	# State-of-the-Art Vendors	# Emerging Vendors	Average Applicability Ratings from Tables 3.5.1 through 3.5.3
Proton Precession Magnetometer	3	0	◔
Optically Pumped Magnetometer (*)	6	1	◕
Single-Axis Fluxgate Magnetometer (*)	7	0	◑
3-Axis Fluxgate Magnetometer	0	3	◕
Fiber-Optic Magnetometer	0	2	◕
Overhauser Effect Magnetometer	1	0	◑
SQUID Magnetometer	0	7	●
Electron Tunneling Magnetometer	0	1	◕
Electromagnetic Induction Sensor (*)	3	3	◔
GPR (land-borne) (*)	10	4	◔
GPR (Airborne)	5	6	◑
UWB Synthetic-Aperture GPR (airborne)	0	6	◑
Stepped FM GPR	0	1	◔
Harmonic GPR	0	1	○
Interferometric Impulse Radar	0	1	◔
Cone Penetrometer	3	0	◔
Transient Acoustic Sensor	1	0	○
Seismic	0	0	◔
Ultrasonic	0	0	◔
Acoustic Imaging	0	3	◔
Visible Imaging (*)	2	1	○
Infrared Radiometry (*)	13	0	○
Infrared Imaging Spectrometry	0	1	○
Millimeter Wave Radiometry	1	0	○
2-D LIDAR (*)	2	1	○
3-D LIDAR (LADAR)	0	2	○
Line Spectra LIDAR	0	1	○
Nuclear Technology (non-metallic only)	0	6	◑
Multi-sensor platform	1	3	--
Other Related Technologies	3	3	--

Scale: ○ ◔ ◑ ◕ ●

Poor Fair Most Applicable

(*) This technology currently in use by the Corps of Engineers

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Section 5

VENDOR INDEX

This table summarizes the vendors mentioned in the entire document by company name.

Table 5.1 Company Name vs. Product Type

Company Name	Product Type	Key Contact and Phone Number	Refer to Section for Detailed Info	Page Number
2G Enterprises	SQUID magnetometers	(415) 965-0500	4.2.1.2.1	195
Agema	IR Sensors	Mike McGinn (714) 379-0282	4.1.6.1	174
Airborne Environmental Surveys	GPR	Robert Cameron (805) 922-1424	4.1.3.2.1	165
Amber / Raytheon	IR Sensors	Charles King, Jr. (805) 683-6621	4.1.6.2	175
American Underwater Search and Survey Ltd.	GPR	John Fish (508) 564-6500	4.1.3.1.1	158
Analytical Spectral Devices, Inc. (ASD)	IR spectro-radiometer	David Hatchell (303) 444-6522	4.1.6.3	176
Applied Physics Systems	Single-axis fluxgate magnetometers	Bob Goodman (415) 965-0500	4.1.1.3.1	148
Applied Physics Systems	SQUID magnetometers	Bob Goodman (415) 965-0500	4.2.1.2.2	195
Applied Physics Systems	3-axis fluxgate magnetometers	Bob Goodman (415) 965-0500	4.2.1.3.1	201
Applied Research Associates ("ARA")	Seismic Sensors	Jim Eddings (205) 882-9394	4.1.4.1	170
Applied Research Associates	Nuclear Technology	Jim Eddings (505) 881-8074	4.2.8.1	226
Areté Engineering Technologies Corp. (AETC)	Post-Processing Classification Software	Dr. Tom Bell (703) 413-0500	4.2.10.1	232
Army Research Lab ("ARL")	IR Sensors	John Buchbach (703) 704-1261	4.1.6.4	177
Army Research Lab	MMW Radiometry	Joe Nemarich (301) 394-3130	4.1.7.1	184
Army Research Lab	GPR	John McCorkle (301) 394-2530	4.2.3.1.1	187
Army Research Lab ("ARL")	Acoustic Sensors,	John Eicke (301) 394-2620	4.2.4.1	209
Army Research Lab	LIDAR	Dr. Zoltan Sztankay (301) 394-3130	4.2.7.1	218
Australian Defense Industries, Ltd.	Optically pumped magnetometers	John Marley (US Rep.) (703) 243-6100	4.1.1.2.1	142
Bales Scientific	IR Sensors	Chip Bishop (510) 945-0144	4.1.6.5	178

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Company Name	Product Type	Key Contact and Phone Number	Refer to Section for Detailed Info	Page Number
Ballena Systems Corp.	GPR	Dr. Kendall Casey (510) 460-3740	4.1.10.1	188
Ballena Systems Corp.	Electromagnetic induction sensors	Dr. Kendall Casey (510) 460-3740	4.2.2.1	206
Ballena Systems Corp.	Nuclear Technology	Dr. Kendall Casey (510) 460-3751	4.2.8.2	226
Ballena Systems Corp.	Advanced Signal Processing	Dr. Kendall Casey (510) 460-3751	4.2.10.2	233
Battelle Inc.	GPR, Multi-sensor platform	Dr. Keith Shubert (614) 424-4916	4.2.3.1.2 4.2.9.1	209, 229
Bison Instruments	Single-axis fluxgate magnetometers	Bret Smith (612) 926-1846	4.1.1.3.2	149
Chemrad Corp.	Single-axis fluxgate magnetometers	Mike Blair Bob Hifield	4.1.10.2	189
Cincinnati Electronics	IR Sensors	Paul Tiven (513) 573-6275	4.1.6.6	178
CNR Istituto di Elettronica Quantistica	Line-Spectra LIDAR (research)	(none)	4.2.7.2	224
Coastal Systems Station	SQUID magnetometers	Gary Kekelis (904) 234-4281	4.2.1.2.3	186
Coastal Systems Station	3-axis fluxgate magnetometers	Gary Kekelis (904) 234-4281	4.2.1.3.2	225
Cold Regions Research and Engineering Laboratory ("CRREL")	GPR	Austin Kovacs (603) 646-4100 x4411	4.1.3.1.2	158
Coleman Research Corp.	GPR	Bill Steinway (407) 352-3700 x1049	4.2.3.2.1	214
Conductus, Inc.	SQUID magnetometers	Stephen Garrison (408) 737-6759	4.2.1.2.4	197
Dean Consulting & Research	GPR	Arnold Dean (802) 649-2202	4.1.10.3	190
Dorex	IR Sensors	Mark Yoshihara (714) 639-0700	4.1.6.7	179
Dynamic Devices and Systems, Inc.	Acoustic imaging	Brian Hodges (410) 744-2424	4.2.4.2.1	219
Earth Tech Corp.	Cone Penetrometer	Gerry Boehm (714) 842-7011	4.1.4.2	171
Environmental Research Institute of Michigan ("ERIM")	GPR	David Spector (313) 994-1200 x2452	4.1.3.2.2	166
Environmental Research Institute of Michigan ("ERIM")	Visible Imaging`	David Spector (313) 994-1200	4.1.5.1	173
FIT (Germany; name too large for table)	SQUID magnetometers	Prof. Dr.-Ing. J. H. Hinken 011 49 50 63 89-580	4.2.1.2.5	198
FOA (Sweden)	GPR	Dr. Hans Hellsten +46 13 11 8000	4.2.3.2.2	215
Foerster Instruments	Single-axis fluxgate magnetometers	Cheryl Hodnicki (412) 788-8976	4.1.1.3.3	149

Company Name	Product Type	Key Contact and Phone Number	Refer to Section for Detailed Info	Page Number
GEM Systems	Proton precession magnetometers	Ivan Hrvoic (416) 764-8008	4.1.1.1.1	140
GEM Systems	Optically pumped magnetometer	Ivan Hrvoic (416) 764-8008	4.1.1.2.2	144
Geo-Centers	Single-axis fluxgate magnetometers	Fenoy Butler (301) 292-1010	4.1.1.3.4	150
Geometrics	Proton precession and optically pumped magnetometer	Ross Johnson (sales) (408) 734-4616	4.1.1.1.2, 4.1.1.2.3	141 145
Geonex Aerodat	Optically pumped magnetometers	Doug Pitcher (905) 671-2446	4.1.1.2.4	146
Geonex Aerodat	EM Sensors	Doug Pitcher (905) 671-2446	4.1.2.1	154
Geonics, Ltd.	Electromagnetic Induction	Miro Bosna (905) 670-9580	4.1.2.2	155
Geophysical & Environmental Research Corp.	Multi-channel IR scanners	Mark Westfield (914) 677-6100	4.1.6.8	180
Geophysical Survey Systems, Inc. ("GSSI")	GPR	Dan Delea (603) 893-1109	4.1.3.1.3	159
GeoRadar, Inc.	GPR	Doug Crice (408) 867-3792	4.1.3.1.4	160
Geoscience / ABEM	GPR	Olof Forslund +46 953 10074	4.1.3.1.5	161
Inframetrics	IR Sensors	John Keane (508) 670-5555	4.1.6.9	180
Jet Propulsion Laboratory	GPR	Walt Brown (818) 354-2110	4.1.3.2.3	166
Jet Propulsion Laboratory	Visible Imaging	Rob Green (818) 354-9136	4.1.5.2	173
Jet Propulsion Laboratory	IR Sensors	Rob Green (818) 354-9136	4.1.6.10, 4.2.5.1, 4.2.6.1	181 221 222
Jet Propulsion Laboratory	Electron tunneling magnetometers	Linda Miller (818) 354-0982	4.2.1.4.1	203
Jet Propulsion Laboratory	Nuclear Trace-Species Detection System	Dr. Ara Chutjian (818) 354-7012	4.2.8.3	227
Kaman Aerospace Corp.	LIDAR	Melvin P. French (203) 243-7085; Dr. Bobby Ulich (602) 295-2101	4.1.8.1.1	185
Lawrence Livermore National Laboratory	UWB GPR	Paul Sargis (510) 422-1100	4.1.3.1.6	162
Lawrence Livermore National Laboratory	IR Sensors	Nancy Del Grande (510) 422-1010	4.1.6.11	182
Lincoln Lab / MIT	GPR	Ted Groesch (617) 981-0130	4.2.3.1.4	211
Loral / IBM	SQUID magnetometers	Fred Sulmer (703) 367-4374	4.2.1.2.6	199
Loral Defense Systems	GPR / Harmonic Radar	Jim Haskins (602) 925-7000	4.2.3.3.1	216

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Company Name	Product Type	Key Contact and Phone Number	Refer to Section for Detailed Info	Page Number
Mirage Systems	GPR	Roger Druhan (408) 733-3200	4.2.3.1.3	210
Naval Research Laboratory ("NRL")	Fiber optic magnetometers	Dr. Frank Bucholtz (202) 767-5369	4.2.1.5.1	204
Nichols Research Corp.	3-axis fluxgate magnetometers	Pete Gray (205) 883-1140	4.2.9.2	229
Oak Ridge National Laboratory	Advanced Signal Processing	Joe Dooley (615) 576-1861	4.2.10.3	233
Ohio State University	GPR	Dr. Jonathan Young (513) 292-6657	4.2.3.1.5	211
Optical Technologies Inc.	Fiber optic magnetometers	Robert Einzig (703) 478-0844	4.2.1.5.2	204
Optronic Laboratories	IR spectro-radiometer	William Schneider (407) 422-3171	4.1.6.12	183
Penetrator	GPR	Tony Alongi (716) 731-4369	4.1.3.1.7	162
Pulse Radars, Inc.	GPR	C.T. Wells (713) 977-0557	4.1.3.1.8	163
Pylon Electronics	Electromagnetic Induction	E. Stack Gately (703) 524-4551	4.1.2.3	156
Quantum Design / Magnetics	Optically pumped magnetometers	Dr. Bill Avrin (619) 481-4400	4.2.1.1.1	194
Quantum Design / Magnetics	SQUID magnetometers	Dr. Bill Avrin (619) 481-4400	4.2.1.2.7	200
Quantum Design / Magnetics	Electromagnetic induction sensors	Dr. Andrew Hibbs (619) 481-4400	4.2.2.3.1	207
Quantum Design / Magnetics	Nuclear Technology	Dr. Bill Avrin (619) 481-4400	4.2.8.4	227
Sage Earth Science (EG&G Idaho)	Single-axis fluxgate magnetometers	Glen Carpenter (208) 526-4166	4.1.1.3.5	151
Schonstedt Instruments	Single-axis fluxgate magnetometers	O.K. Davis (703) 471-1050	4.1.1.3.6	152
Schwartz Electro-Optics	LIDAR	Dr. Peter Moulton (508) 371-2299	4.2.7.3	224
Science Applications International Corp.	Interferometric Impulse Radar	Rich Sutton (703) 821-4300 x4402	4.2.3.4.1	217
Science Applications International Corp.	Multi-sensor platform for mine detection	Dr. Joseph Bendahan (408) 727-0607	4.2.9.3	230
Scintrex	Proton precession magnetometers	Richard Lachapelle (905) 669-2280	4.1.1.1.3	142
Scintrex	Optically pumped magnetometers	Richard Lachapelle (905) 669-2280	4.1.1.2.5	147
Sensors and Software, Inc.	GPR	Peter Annan (416) 624-8909	4.1.3.1.9	164
Stanford Research Institute	GPR	Roger S. Vickers (415) 326-6200	4.1.3.2.4	167, 168
Stratigraphics	Cone Penetrometer	Andrew Strutynsky (708) 790-4615	4.1.4.3	172
Tetra Corp.	Acoustic imaging	William Moeny (505) 345-8623	4.2.4.2.2	218

Company Name	Product Type	Key Contact and Phone Number	Refer to Section for Detailed Info	Page Number
Thermetics Detection Inc.	Nuclear Technology	Barley Dutton (508) 251-2000	4.2.8.5	228
Time Domain Systems, Inc.	GPR	Larry Fullerton (205) 837-6662	4.2.3.1.6	212
University of Arizona	EM	Dr. Ben Sternberg (602) 621-2439	4.2.2.2	206
Varian Associates	Mk22 former manufacturer	(415) 493-4000	4.1.1.2.6	147
Waterways Experimental Station ("WES")	LIDAR	Jay Bennett (601) 634-3924	4.2.7.4 4.1.8.1.2	225 186

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APPENDICES

Appendix A:	Acronyms/Glossary
Appendix B:	Bibliography
Appendix C:	Soil Type Definitions

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APPENDIX A: ACRONYMS/GLOSSARY

AC	Alternating Current
AETC	Aretė Engineering Technologies Corp.
AOTF	acoustic-optical tunable filters
APL	Applied Physics Laboratory
APS	Active Pixel Sensor; one type of modern light-sensing device. (Also stands for Applied Physics Systems)
ARL	Army Research Lab
ARPA	Advanced Research Projects Agency, a research arm of the Defense Department that traditionally takes on high-risk/high yield research.
ASD	Analytical Spectral Devices (Inc.)
AT&T	American Telephone and Telegraph
AVIRIS	Airborne Visual and Infrared Imaging Spectrometer
Azimuth resolution	The along-track direction resolution of a side-looking synthetic-aperture radar.
BAA	Broad Area Announcement
Brew ster angle	The arctangent of the ratio of the index of refraction of the second medium to the first. Brewster angles are used to predict the directions of the reflected and refracted waves when the waves make the transition from one medium to another.
c	Speed of light and electromagnetic radiation, = 3×10^8 meters per second
C	Celsius, a metric measure of thermal temperature.
CARABAS	Coherent All Radio Band Sensing (Radar)
CCD	Charge-Coupled Device; the active sensing element in modern digital imaging systems.

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CEHND	Corps of Engineers, HuNtsville Division
COTS	Commercial off-the-shelf; can be readily purchased and put to use immediately.
CPT	Standard abbreviation for Cone Penetrometer
CRT	Cathode Ray Tube, usually referring to a computer monitor.
CSM	Chemical surety material
CSS	Coastal Systems Station, a unit of the Naval Surface Warfare Center
d	Variable representing antenna length when doing GPR calculations.
dB	Decibels, a logarithmic unit of measure for sound pressure and signal intensity.
DC	Direct Current. In the case of the DC SQUID magnetometer, it means it employs no high-frequency oscillating components.
depression angle	The angle subtended between the antenna of a synthetic-aperture radar and the horizontal direction.
DoD	Department of Defense
DoE	Department of Energy
DRES	Defense Research Establishment Suffield
ε	Symbol for permittivity. Permittivity is defined as a measure of how well or how much a material or substance slows down an electromagnetic wave.
EM	ElectroMagnetic, usually referring to electromagnetic induction
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
EOD	Explosive Ordnance Detection

ERIM	Environmental Research Institute of Michigan
EXDEP	Explosive Detection with Energetic Photons, the new name for MIDEP.
ϕ	Symbol for frequency, measured in cycles per second (Hertz)
FAA	Federal Aviation Administration
FASCAM	Family of Scatterable Mines
FFT	Fast Fourier Transform
FIR	Far Infra-Red
FIT	Forschungsgesellschaft für Informationstechnik (mbH)
FLL	Flux-locked loop
FM	Frequency Modulated, referring to the radio frequency band assigned to commercial radio.
FM-CW	Frequency Modulated, Continuous-Wave - used to describe a type of ground-penetrating radar.
FPR	Foliage-penetrating radar
FUDS	Formerly Used Defense Sites
gamma (γ)	gamma, a standard unit of magnetic field measurement. One gamma (γ) is equal to 10^{-9} Tesla, or 1 nT.
GHz	Gigahertz, meaning 10^{12} cycles per second.
GIS	Geographical information system; a computer-based application designed for easy map generation and correlation and visualization of data.
GPR	Ground-Penetrating Radar
GPS	global positioning satellite, an accurate method of determining exact geographical position using satellites and a special handheld receiver.

HH	Shorthand for Horizontal polarization; when the electric field is parallel to the plane of incidence. (In the GPR sense, the plane of incidence is the ground).
Hz	Hertz, the term used to measure frequency. Equivalent to the phrase "cycles per second".
In-Phase Signal	Term used to describe when the transmitted and received signals are of the same amplitude without phase shift
IFOV	Instantaneous field of view
IR	Infrared
JPL	Jet Propulsion Laboratory
km	kilometer
λ	Symbol for wavelength, measured in meters.
Larmor frequency	The natural resonance frequency within an atom at which precession occurs due to energy state transition excited by an external pumping beam. This phenomenon is used as the basis for detecting external magnetic field intensities.
LCD	Liquid Crystal Display
LIDAR	LIght Detection And Ranging
LIF	laser-induced fluorescence
LLNL	Lawrence Livermore National Laboratories
μm	micrometer, equal to 10^{-6} meters
m	meter
Magnetostrictive material	A magnetic-field-sensitive material that contracts in the presence of an external magnetic field. When this material is coated on the surface of optical fiber, changes in magnetic fields alter the optical transmission properties of the fiber, which can result in a change of fringe pattern when combined with a stable reference. Detecting such fringe changes infers the presence of a magnetic field; this is the principle behind the Mach-Zehnder fiber optic magnetometer.
MCX	Mandatory Center of Expertise

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MDL	Microdevices Laboratory
MeV	Mega electron volt, a convenient unit for measuring energy in nuclear physics.
MHz	Megahertz, equal to 10^6 cycles per second.
MIDEP	MIne Detection with Energetic Photons, more recently renamed EXDEP.
MIT	Massachusetts Institute of Technology
mm	millimeter, equal to 10^{-3} meters.
MMW	Millimeter Wave - referring to the frequency band of operation.
MW	Mega Watts
MWIR	Mid-wave infrared
NASA	National Aeronautics and Space Administration
NIR	Near infrared
NMR	Nuclear Magnetic Resonance
NRC	Nichols Research Corp.
NRL	Naval Research Laboratory
NSWC	Naval Surface Warfare Center
nT	nano-Telsa, a very small (10^{-9}) measurement of a magnetic field. 1 nT = 1 gamma = 10^{-9} Webers/m^2
NTG	Neutron Thermalization Gauge
OEW	Ordnance and Explosive Waste
PC	Personal Computer
permittivity (ε)	A measure of how well or how much a material or substance slows down an electromagnetic wave.

PRI	Pulse Radars, Inc.
quadrature signals	The nonlinear second-order phase difference present between the transmitted signal and the received signal of an airborne (or spaceborne) electromagnetic sensor. This signal is used to measure the ground conductance.
R&D	Research and development
RAC	Risk Assessment Code. This is the label used by the Corps of Engineers to prioritize their base cleanups. A RAC 1 site is given top priority.
Radar	Radio Detection and Ranging; a means of sensing which sends bursts of electromagnetic energy and senses its reflection.
Radar Return	The radar's pulsed energy which returns from the terrain.
range gate	A technique for noise suppression which involves turning on the receiver only during the time that a return signal is expected.
range resolution	The resolution in the direction the radar dish antenna is pointing. The shorter the radar's pulse length, the higher the resolution.
RCS	Remote Characterization System
READ	Reversal Electron Attachment Detection
REMIDS	Remote Minefield Detection System
RF	Radio-frequency, usually referring to a portion to the electromagnetic spectrum.
S	Variable representing slant-range distance when doing GPR calculations.
SAIC	Science Applications International Corp.
SAR	Synthetic-aperture Radar. A technique for obtaining high-resolution radar images without having to use a full-sized antenna.
Siemen, (σ)	Conductivity of a material, which is the inverse of its resistivity, ρ. Units for Siemens are 1/ohm•meter.

sin	Short for Sine, a trigonometric function that takes an angle as its argument and returns a value between -1 and +1.
slant range distance	The distance between an airborne (or spaceborne) side-looking radar and its target.
SLAR	Side-looking airborne radar
SNR	Signal-to-noise ratio. a common method of measuring instrument sensitivity.
SQUID	Superconducting quantum interference device
SRI	Stanford Research Institute
STOLS	Surface Towed Ordnance Locator System
SWIR	Single-wavelength infrared
T	Tesla, a standard unit of measurement for magnetic fields. One gamma (γ) is equal to 10^{-9} Tesla, or 1 nT.
τ	Pulse length, measured in seconds. A typical GPR has a pulse length in the nanosecond range.
TIR	Thermal Infra-Red
TIRIS	Thermal Infrared Imaging Spectrometer
TNA	Thermal neutron analysis
USACE	United States Army Corps of Engineers
USRADS	UltraSonic Ranging And Data System
UWB	Ultra Wide Band, referring to the most common type of modern radar systems.
UWBSAR	UltraWide Band Synthetic-Aperture Radar
UXO	UneXploded Ordnance

vertical profiling mode	Radar is operated by looking vertically downward with a 90 degree depression angle. Just as an airborne flashlight would best illuminate the ground best if it were pointing straight down, a GPR can obtain the best readings by having it vertically oriented. The ground coverage is limited to the radar beamwidth.
VG	Vertical Gradient
VLSI	Very Large Scale Integration
VMOD	Vehicle-mounted ordnance detector
VV	Vertical polarization, when the magnetic field is parallel to the plane of incidence. (In the GPR sense, the plane of incidence is the ground).
WES	Waterways Experimental Station

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APPENDIX B: REFERENCES

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APPENDIX C: SOIL TYPE DEFINITIONS

These definitions are of a finer resolution than the 11 soil types defined in Section 3.3.1.

Table C 1. Definitions of Major Soil Groups

Alfisol	Medium-to-high in bases (base saturation at pH 8.2) and have gray-to-brown surface horizon and subsurface horizons of clay accumulations; usually moist but during the warm season of the year are dry part of the time.
Aridisol	Soil-forming strata; low in organic matter; arid, never moist as long as three consecutive months.
Entisol	Soils that have no pedogenic horizons.
Histosol	Wet organic (peat and muck) soils; includes soils in which the decomposition of plant residues ranges from highly decomposed to not decomposed; formed in swamps and marshes.
Inceptisol	Soils that have weakly differentiated horizons; materials in the soil have been altered or removed but have not accumulated. These soils are usually moist, but during the warm season of the year some are dry part of the time.
Mollisol	Soils that have thick nearly black organic-rich surface horizons high in bases; formed mostly in subhumid and semiarid warm to cold climates.
Oxisol	Soils that are mixtures principally of kaolin, hydrated oxides, and quartz and that are low in weatherable minerals; formed on gentle or moderate slopes at low or moderate elevations in tropical or subtropical climates.
Spodosol	Soils with low base supply that have in subsurface horizons an accumulation of amorphous materials consisting of organic matter plus compounds of aluminum and usually iron; formed in acid mainly coarse-textured materials in humid and mostly cool or temperate climates.
Ultisol	Soils that are low in bases and have subsurface horizons of clay accumulation; usually moist, but during the warm season of the year, some are dry part of the time.

Vertisol	Clayey soils that have wide, deep cracks when dry; most have distinct wet and dry periods throughout the year.
Misc.	Barren or nearly barren areas that are mainly rock, ice, or salt and some included soils.

In the United States there are only 36 soil subgroups of the major eleven soils, and they are identified in Tables C 2 through C 10. Although there is more refined granularity that quantifies variations within the majority of these subgroups, these differences will generally not have a first-order effect on sensor performance and will be considered only on a site-specific case-by-case basis. There are no major subgroups for either the histosol or the miscellaneous soil groups.

Table C 2. Alfisol soil major subgroups

Aqualfs	Seasonally wet alfisols that have mottles, iron-manganese concentrations, or gray colors
Boralfs	Alfisols of cool to cold regions
Udalfs	Alfisols that are in temperate to tropical regions. Soils are usually moist, but during the warm season of the year may be intermittently dry in some horizons for short periods
Ustalfs	Very similar to udalfs except that during the warm season they are intermittently dry for long periods
Xeralfs	Alfisols that are in climates with rainy winters but dry summers; during the warm season of the year these soils are continually dry for a long period

Table C 3. Aridisol soil major subgroups

Argids	Aridisols that have a horizon in which clay has accumulated with or without alkali (sodium)
Orthids	Aridisols that have accumulations of calcium carbonate, gypsum, or other salts more soluble than gypsum but have no horizon of accumulation of clay. They may have horizons from which some materials have been removed or altered

Table C 4. Entisol soil major subgroups

Aquents	Entisols that are either permanently wet or are seasonally wet and that have mottles or gray colors
Fluvents	Entisols that have organic matter content that decreases irregularly with depth; formed in loamy or clayey alluvial deposits
Orthents	Loamy or clayey entisols that have a regular decrease in organic matter content with depth
Psamments	Entisols that have textures of loamy fine sand or coarser

Table C 5. Inceptisol soil major subgroups

Andepts	Inceptisols that either have formed in ashy (vitric pyroclastic) materials, have low bulk density and large amounts of amorphous materials, or both
Aquepts	Seasonally wet inceptisols that have an organic surface horizon, sodium saturation, mottles, or gray colors
Ochrepts	Inceptisols that have formed in materials with crystalline clay minerals, have light-colored surface horizons, and have altered subsurface horizons that have lost mineral materials
Tropepts	Inceptisols of tropical climates
Umbrepts	Inceptisols with crystalline clay minerals, thick dark-colored surface horizons, and altered subsurface horizons that have lost mineral materials and that are low in bases

Table C 6. Mollisol soil major subgroups

Albolls	Mollisols of flat places and high closed depressions. They have a seasonal perched water table and a nearly black surface horizon underlain by a bleached (white) mottled horizon over a horizon of clay accumulation that has mottles or gray colors
Aquolls	Seasonally wet mollisols that have a thick nearly black surface horizon and gray subsurface horizons
Borolls	Mollisols of cool and cold regions; most have a black surface horizon

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Rendolls	Mollisols with subsurface horizons that have large amounts of calcium carbonate but no accumulation of clay
Udolls	Mollisols of temperate climates; usually moist and have no horizon in which either calcium carbonate or gypsum has accumulated
Ustolls	Mollisols that are mostly in semiarid regions. During the warm season of the year, these soils are intermittently dry for a long period or have subsurface horizons in which salts or carbonates have accumulated
Xerolls	Mollisols that are in climates with rainy winters but dry summers; during the warm season of the year, these soils are continually dry for a long period

Table C 7. Oxisol soil major subgroups

Humox	Oxisols that are moist all or most of the time; have a high content of organic matter but are low in bases
Orthox	Similar to humox but have moderate to low content of organic matter
Ustox	Oxisols that are continually dry in some part of the soil for a long period during the year

Table C 8. Spodosol soil major subgroups

Aquods	Seasonally wet spodosols; formed in humid climates of arctic to tropical regions
Orthods	Spodosols that have a horizon in which organic matter plus compounds of iron and aluminum have accumulated

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Table C 9. Ultisol soil major subgroups

Aquults	Seasonally wet ultisols that have mottles, iron-manganese concretions, or gray colors
Humults	Ultisols that have a high content of organic matter; formed in temperate or tropical climates that have high amounts of rainfall throughout the year
Udults	Ultisols that are usually moist and that are relatively low in organic matter in the subsurface horizons; formed in humid climates that short or no dry periods during the year
Xerults	Ultisols that are relatively low in organic matter in the subsurface horizons. They are in climates with rainy winters but dry summers; during the warm season of the year, these soils are continually dry for a long period

Table C 10. Vertisol soil major subgroup

Torrerts	Vertisols that are usually dry and have wide, deep cracks that remain open throughout the year in most years
Uderts	Vertisols that are usually moist. they have wide, deep cracks that usually open and close one or more times during the year but do not remain open continuously for more than two months or intermittently for periods that total more than three months
Usterts	Vertisols that have wide, deep cracks that usually open and close more than once during the year and remain open intermittently for periods that total more than three months but do not remain open continuously throughout the year
Xererts	Vertisols that have wide, deep cracks that open and close once each year and remain open continuously for more than two months

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